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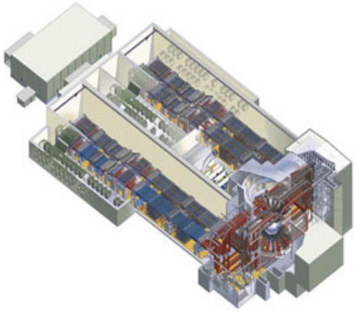
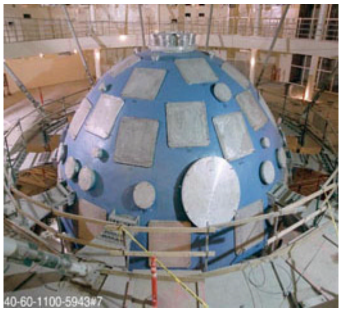
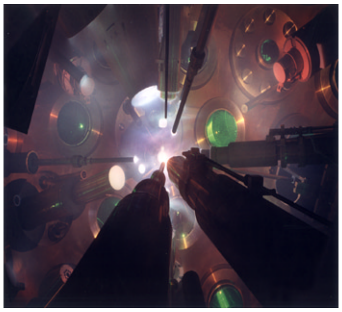


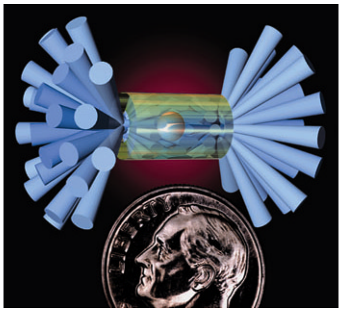
High-Energy-Density Physics Study Report

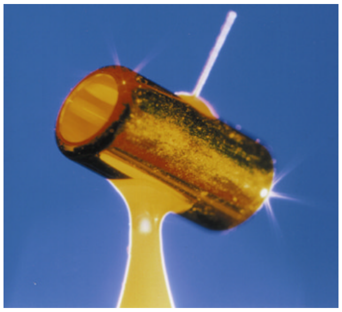
A Comprehensive Study of the Role of High-Energy-Density Physics in the Stockpile Stewardship Program

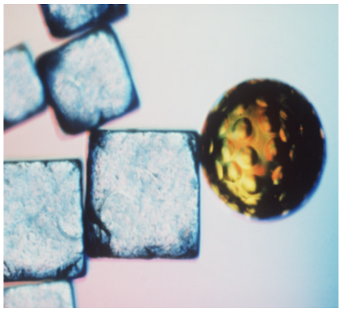
April 6, 2001

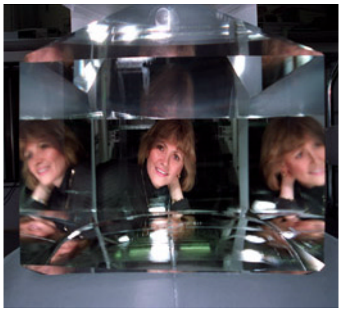












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Preface

This report documents the results of a Defense Programs study on the High-Energy-Density Physics Program within the Stockpile Stewardship Program. I would like to thank those who contributed to the completion of this study. This includes the study panel members, the federal staff, and senior laboratory participants who are listed in the report. I would also like to acknowledge Headquarters' and laboratories' staff who devoted considerable effort to this, including David Crandall, Christopher Keane, Terri Batuyong, Joan Bersie, Steve Binkley, Melissa Cray, Allan Hauer, Robert Kauffman Walter Kirchner, Keith Matzen, Hank O'Brien, Joe Polito, Deb Rubin-Bice, Michael Sorem, and Charles Verdon.

Thanks to all for a job well done.

Thomas F. Gioconda

Thomas F. Gioconda
Brigadier General, USAF
Acting Deputy Administrator
Defense Programs
National Nuclear Security Administration

Executive Summary

In its fiscal year (FY) 2001 Energy and Water Development Appropriation, Congress directed the National Nuclear Security Administration (NNSA) to complete a study that "includes conclusions as to whether the full-scale NIF [National Ignition Facility] is required in order to maintain the safety and reliability of the current nuclear weapons stockpile, and whether alternatives to the NIF could achieve the objective of maintaining the safety and reliability of the current nuclear weapons stockpile." To meet this requirement, the NNSA has conducted a detailed study of the role of high-energy-density physics (HEDP) and NIF in the Stockpile Stewardship Program (SSP). The principal finding of this study is that a vital HEDP Program is an essential component of the SSP. Based on this finding, the Office of Defense Programs (DP) recommends the continuation of the baseline HEDP Program, including 192-beam NIF, with the goal of achieving ignition.

The Stockpile Stewardship Program is in place and is successfully sustaining confidence in the U.S. nuclear weapons stockpile. Significant stockpile actions have been accomplished since its inception, including the development and production of the B61-11, an earth penetrating strategic bomb to replace the aging B53. More actions are currently underway, such as the W87 Life Extension Program (LEP). Several actions are in planning and development stages, including manufacture and certification of W88 pits and LEPs for the W76-1, the W80-2/3 warheads, and the B61-7/11 bomb. In all of these stockpile actions, new tools developed by the SSP have been used to identify issues, analyze potential impacts, develop solutions, implement changes and, in the case of completed stockpile actions, support continued certification of the weapons. This experience has reinforced SSP requirements for future developments in both manufacturing and scientific capabilities. Among the requirements is a need for a strong HEDP Program.

In the FY 2001 Energy and Water Development Appropriation Act (P.L. 106-377, Sect. 1(2)(2), published as Appendix B), the NNSA was directed to send to Congress a certification that "(d) includes a study of requirements for and alternatives to a 192 beam ignition facility for maintaining the safety and reliability of the current nuclear weapons stockpile." To make this assessment, the NNSA undertook a comprehensive study of the role of HEDP in the SSP. The purpose of the study was to understand and document the importance of HEDP and its role in certification of the safety, security and reliability of U.S. nuclear weapons, now and in the future, without recourse to underground nuclear testing. The study reviewed the requirements for HEDP in the SSP, reassessed the current baseline program against those requirements, and considered whether alternatives to that baseline, proposed by the three NNSA national laboratories, could better address the requirements than the current baseline.

The SSP was established in response to the FY 1994 National Defense Authorization Act (P.L. 103-160, Sect. 3138), which called on the Secretary of Energy to "establish a stewardship program to ensure the preservation of the core intellectual and technical competencies of the United States in nuclear weapons." In the absence of nuclear testing, the SSP must:
1) support a focused, multifaceted program to increase the understanding of the enduring stockpile; 2) predict, detect, and

evaluate potential problems due to the aging of the stockpile;
3) refurbish and remanufacture weapons and components, as required; and
4) maintain the science and engineering institutions needed to support the nation's nuclear deterrent, now and in the future.
The principal outcomes of the SSP are confidence in safety, security, and reliability of U.S. nuclear weapons and a cadre of nuclear-skilled personnel, underpinning nuclear deterrence.

The SSP has a substantial science program focused on addressing these goals. It includes a balanced program of research and development in high-energy-density physics, hydrodynamics, engineering science, materials science, and advanced simulation and computing. Although the NNSA national laboratories have different approaches for certifying the stockpile, they agree that maintaining a balanced program of research underpins all present and future certification decisions. To a large extent, the fact that the laboratories have differing certification approaches, relying on differing use of capabilities and facilities in these science programs, strengthens the certification of the stockpile and the cadre of personnel involved in these activities.
The NNSA national laboratories agree that a strong and diverse HEDP Program is an essential component of the SSP. An excellent understanding of high-energy-density physics is required to understand the operation of nuclear weapons. The fundamental requirements for the baseline HEDP Program are driven by meeting the needs of the stockpile and by a commitment to related, broader national scientific interests. Based on these requirements, the HEDP Program has developed a set of strategic goals in the following areas: weapons physics, ignition, high yield, radiation effects, basic science, and supporting technologies. These goals include

- Execution of high-energy-density weapons physics experiments required by the SSP for ensuring the safety, security, and reliability of the nuclear stockpile.
- Achievement of ignition at NIF by 2010.
- Maintaining outstanding talent in the HEDP Program by providing recruitment and training opportunities.
- Completion of the NIF Project and the Z-backlighter on the current cost and schedule baselines.
- Development and fabrication of the cryogenic systems and diagnostics required for NIF.
- Development of advanced x-ray sources for nuclear weapons effects testing.
- Development of options, in the 2008-2010 timeframe, for a next-generation, high-yield facility.
- Development of the advanced laser and pulsed-power technologies required for NIF and a potential next-generation pulsed-power machine, respectively.
- Maintaining U.S. preeminence in high-energy-density (HED) science.
- Supporting broader, national scientific goals, which require involvement of the DP HEDP Program.

A complementary and diverse set of experimental facilities is planned across a number of institutions to provide capabilities for experimental access to the high-energy-density physics regime.

Presently, there are seven principal HEDP facilities spanning both laser and pulsed-power capabilities, including Omega at the University of Rochester Laboratory for Laser Energetics (UR/LLE), Z and Saturn at Sandia National Laboratories (SNL), Trident at Los Alamos National Laboratory (LANL), Nike at the Naval Research Laboratory (NRL), Atlas, which is being moved from LANL to the Nevada Test Site (NTS), and Janus at Lawrence Livermore National Laboratory (LLNL). The flagship facility in this program, presently under construction at LLNL, is NIF. The NIF Project baseline provides for delivery of 1.8 megajoules of energy from 192 laser beams at the conclusion of the construction project in FY 2008, with first light from the facility in FY 2004. The bulk of research at NIF will be divided between advancing the understanding of HED weapons physics and achievement of ignition. The HEDP Program is national in scope, and includes participation by the University of Rochester's Laboratory for Laser Energetics, NRL, a number of universities, and other institutions, in addition to the three NNSA national laboratories. The resources needed to maintain the pace and vitality of this baseline HEDP Program amount to just over a half billion dollars per year.

Within the HEDP Program, there have been significant scientific advances during the past decade, including research achievements in target and laser physics, that have underpinned progress towards completion of NIF and, potentially, the achievement of ignition. A diverse set of experiments at HEDP facilities has advanced the understanding of weapons-physics phenomena. Advanced calculations have been performed, estimating the energy requirement for achievement of fusion ignition and burn in the laboratory. An ever-expanding range of HEDP basic science studies has advanced scientific understanding in astrophysics, plasma physics, and atomic physics. Advances in areas of supporting HEDP technologies span cryogenics, pulsed power, and diagnostic development.

To determine if the HEDP Program is properly optimized to meet the needs of DP's mission, DP invited senior members of the defense and scientific communities to examine high-energy-density activities conducted throughout the SSP. These study panel members were asked specifically to assess the role of high-energy-density physics within the SSP, and to examine the facilities and program elements within the HEDP Program to assure that the goals of the SSP are met in the near and long term. Two areas that were not included directly in this study were HEDP activities within the Advanced Simulation and Computing Campaign and the cost considerations associated with developing and operating the necessary experimental, computational, manufacturing, and production capabilities required for the SSP.

The NNSA national laboratories were asked to submit alternatives to the baseline HEDP Program that could better serve the needs of the SSP. The alternatives presented included pauses or stops in NIF construction at 48, 96, and 120 beams, a refurbishment of the Z machine at SNL, and adding an engineering demonstration milestone to the NIF Project after first light. The alternatives were assessed at a workshop held at SNL's Livermore site, January 30-February 2, 2001. The findings presented in this report reflect conclusions reached by DP during the course of the study. Based on these findings, DP has formulated its recommended path forward. This report provides a summary of the current HEDP baseline, its role in the SSP, and resulting findings and recommendations.

Principal Findings of the Study

- **A vital HEDP Program is an essential component of the SSP. The baseline HEDP Program, including completion of the 192-beam NIF, on the approved baseline, meets the SSP requirements and is the appropriate path forward.**

- **Specific DoD Concern:** In the current budget environment, full funding of the science portion of the SSP could put at high risk the ability of the NNSA to refurbish the production infrastructure and meet the current schedules for life extensions of the W76, W80, and B61.

- The different certification approaches of the laboratories all require enhanced understanding of weapon behavior embodied in the HEDP Program and the entire SSP. Some progress has been made toward development of quantitative metrics for stockpile assessment and certification.

- Significant progress has been made in outlining a detailed experimental weapons physics program, to be conducted at NIF.

- Ignition is an important goal for the HEDP Program, the SSP, and the national scientific community.

- Alternatives to the current NIF Project baseline that include significant delays or pauses would have severe negative consequences for the NIF Project, the HEDP Program, and the SSP.

- The proposed Z refurbishment shows promise for enhancing the HEDP Program, especially in the near term, but it cannot provide the same capabilities as NIF.

- Balance and affordability of the HEDP Program, within the SSP, are significant concerns.

- While more detailed analysis is required, the use of special nuclear materials at NIF may be important to maximize the value of the facility to the SSP.

- People are the most important asset of the NNSA. The HEDP Program and NIF play an important role in attracting, training, and retaining the outstanding talent who will serve as the next generation of stockpile stewards.

- A truly national program to utilize NIF, that builds on the existing user base, is needed.

Principal Recommendations of Defense Programs

- **DP recommends that the NNSA continue with the baseline HEDP Program, including Omega, Z, and the 192-beam NIF, including the goal of ignition.**
- DP strongly recommends that the NIF Project continue along the current baseline and maintain the goal of completing the full set of 192 beams.
- Semi-annual reviews of the NIF Project should continue. NNSA and its laboratories should work together to define mutually acceptable project and HEDP Program milestones to monitor overall NIF progress and encourage formation of a national program.
- NNSA should support the robust technical program that is required to meet the increasing challenges of the assessment and certification program that will arise due to aging, remanufacturing, and the discovery of design flaws within the stockpile. Quantitative metrics for assessment and certification should continue to be developed, to increase confidence in the stockpile.
- The weapons physics material presented by LLNL, at the HEDP Workshop, forms a solid basis for further discussion and should be peer-reviewed in detail.
- The five-year planning process within DP and NNSA should be broadened and instituted as a permanent, ongoing, strategic planning effort used to aid DP, NNSA, and the laboratories in assessing program balance and managing the SSP at a top level.
- The proposed refurbishment of Z shows promise and should be formally considered by the NNSA for inclusion in the baseline HEDP Program.
- The possibility of using special nuclear materials in experiments at NIF and on Z should be examined, consistent with technical considerations, resource requirements, legal requirements, and safety and environmental issues and regulations.
- The draft NIF Governance Plan should be developed for comment by April 30, 2001, as per recent direction from the NNSA.
- The NNSA should develop a focused recruiting program, based on NIF and other major HEDP/SSP capabilities.

CHAPTER 1

Study Purpose and Methodology

Study Purpose and Methodology

This report documents a comprehensive study, initiated by the Deputy Administrator for the Office of Defense Programs (DP), of the role of high-energy-density physics (HEDP) in the Stockpile Stewardship Program (SSP). The purpose of the study was to understand and document the importance of HEDP, within the SSP, and to understand its role in certification of the safety, security, and reliability of U.S. nuclear weapons, now and into the future, without recourse to nuclear testing. The study responds to the requirement imposed in the fiscal year (FY) 2001 Energy and Water Development Appropriations Conference Act (P.L. 106-377, Sect. 1(2)(2), published as Appendix B), which directed that the Administrator of the National Nuclear Security Administration (NNSA) send to Congress a certification that:

> "(d) includes a study of requirements for and alternatives to a 192 beam ignition facility for maintaining the safety and reliability of the current nuclear weapons stockpile."

The study reviewed the requirements for HEDP within the SSP, assessed the current baseline program against those requirements, and considered whether alternatives to that baseline, proposed by the three NNSA national laboratories could address the requirements better than the current baseline HEDP Program.

1.1 Workshop Methodology

The centerpiece of the study was a workshop held at Sandia National Laboratories' California site January 30-February 2, 2001. The workshop agenda can be found in Appendix A. At the workshop, the laboratories presented their approaches to certification and identified the requirements for the HEDP Program that they felt were necessary to certify the safety and reliability of the nuclear weapons stockpile. The workshop study panel members assessed the weapons-physics applications of the HEDP baseline and the alternatives that were presented against the requirements presented by the laboratories, and individually made their findings and recommendations to DP.

The study covered the HEDP experimental program and facilities, with NIF and the proposed alternatives as the focus. The workshop brought together NNSA and laboratory leadership, study panel members from various government agencies, and NNSA and laboratory technical personnel. A set of questions to guide the study panel members was prepared and distributed, along with a document describing the baseline HEDP Program, which can be found in Appendix B. Following the workshop presentations and discussions, the study panel members prepared their individual opinions and submitted them to DP. From discussions during the course of the study, and input from the laboratories, study panel members, and DP management, DP has reached conclusions regarding HEDP and NIF.

These conclusions and subsequent DP recommendations can be found in Chapter 6 of this report. They will be used by the NNSA as input for a certification to Congress.

1.2 Questions Posed to Focus the Workshop

The following questions were developed to guide presentations and discussion at the workshop.

1. Certification: Without nuclear testing, what is the approach and what are the metrics?
   - What is the strategy and proposed path to assessment and certification without full-scale nuclear testing?
   - What are the metrics that indicate when SSP, and its HEDP component, are on a path to success or to failure?
2. Requirements: What are the requirements for HEDP within the SSP?
   - How does the HEDP Program fit into a balanced program of theoretical, computational, and experimental science, as well as manufacturing, for stockpile stewardship?
   - Quantitatively, what HEDP data are required to

     a) continue high confidence, annual certification of the stockpile?

     b) accomplish the planned stockpile Life Extension Programs (LEPs) and resolve Significant Finding Investigations (SFIs)?

     c) continue readiness to support the existing stockpile beyond the currently planned LEPs?

     d) maintain scientific excellence in the SSP?
3. Baseline: How does the baseline HEDP Program meet these requirements?
   - How does NIF help to meet the HEDP requirements for assessment and certification of the stockpile? Consider

     d) Direct stockpile issues,

     e) Development of underlying science, and

     f) Attracting, developing, and retaining a work force that possesses the requisite skills

     g) the importance of the "grand challenge" of achieving ignition in the laboratory.
   - How is the capability of the HEDP Program to meet the needs of the SSP affected or put at risk, as the size of NIF (i.e., number of beams) is reduced, or the installation of beams delayed past that in the current NIF baseline?
4. Alternatives: How do the proposed alternatives meet the requirements?
   - For each proposed alternative, consider

e) How is the assessment and certification strategy changed?

f) What capabilities are provided to the HEDP Program by the alternative?

g) How are the costs of, and risk to, the HEDP Program changed, and what new benefits are introduced?

h) What data exists to support the analysis of costs, benefits, and risks represented by the alternative? How have these data been validated?

5. <u>Recommendations:</u> Recommend a path forward for the HEDP Program.

   - Select a recommended path forward based on the best judgment of the study panel member of the risk and cost to the SSP.

1.3 High-Energy-Density Physics Program Study

NNSA Study Lead

BGen Thomas F. Gioconda†
Acting Deputy Administrator,
Defense Programs
National Nuclear Security Administration
U.S. Department of Energy

Dr. David H. Crandall
Assistant Deputy Administrator for
Research, Development and Simulation
National Nuclear Security Administration
U.S. Department of Energy

Dr. James L. Anderson
Director, Office of the NIF Project
National Nuclear Security Administration
U.S. Department of Energy

Dr. Christopher J. Keane
Acting Director, Division of
Secondaries and Inertial Fusion
National Nuclear Security Administration
U.S. Department of Energy

Mr. James L. Van Fleet
Acting Director, Office of Defense Science
National Nuclear Security Administration
U.S. Department of Energy

Study Panel Members

Dr. Barry Hannah†
Head, Reentry Branch
Navy Strategic Systems Program
U.S. Navy
U.S. Department of Defense

Dr. Ted Hardebeck†*
Chief Scientist
U.S. Strategic Command, J-5B
U.S. Department of Defense

Dr. Hermann A. Grunder
Director
Argonne National Laboratory

Dr. Robert S. Marianelli
Office of Science
U.S. Department of Energy

Dr. Maureen I. McCarthy
Chief Scientist
National Nuclear Security
Administration
U.S. Department of Energy

Dr. Ronald H. McKnight
Office of Fusion Energy Sciences
U.S. Department of Energy

Dr. Billy Mullins
Director, Nuclear Weapons and
Counterproliferation Agency
U. S. Air Force
U. S. Department of Defense

Dr. Jay H. Norman
Deputy Manager, Test and Operations
NNSA Nevada Operations Office
U.S. Department of Energy

Dr. James K. Rice
Director, Energy Components and
Metrology Center
Sandia National Laboratories

Dr. Wayne J. Shotts
Associate Director, Non-proliferation,
Arms Control, and International Security
Lawrence Livermore National Laboratory

Dr. Jon C. Weisheit
Division Director, Applied Physics Division
Los Alamos National Laboratory

Senior Laboratory Participants

Dr. George H. Miller
Associate Director
Lawrence Livermore National Laboratory

Dr. Michael R. Anastasio
Associate Director
Lawrence Livermore National Laboratory

Dr. Thomas O. Hunter
Senior Vice President
Sandia National Laboratories

Dr. Stephen M. Younger
Associate Laboratory Director
Los Alamos National Laboratory

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*Col. David Rehbein attended the workshop for Dr. Ted Hardebeck
†Not present at workshop.

2

CHAPTER 2

The Stockpile Stewardship Program

2

The Stockpile Stewardship Program

The SSP was established in response to the FY 1994 National Defense Authorization Act (P.L. 103-160, Section 3138), which directed the Secretary of Energy to "establish a stewardship program to ensure the preservation of the core intellectual and technical competencies of the United States in nuclear weapons." In the absence of nuclear testing, the SSP must:
1) support a focused, multifaceted program to increase the understanding of the enduring stockpile; 2) predict, detect, and evaluate potential problems due to the aging of the stockpile;
3) modernize, refurbish, and remanufacture weapons and components, as required; and
4) maintain the science, engineering, and production infrastructure required to support the nation's nuclear deterrent, now and in the future. The SSP and its constituent elements have been reviewed extensively since its inception, most recently in the 30-Day Study conducted during the autumn of 1999.[1]

As the civilian steward of the nation's nuclear weapons complex, the NNSA is responsible to the nation for the safety, security, and reliability[2] of the U.S. nuclear arsenal. The Department of Defense (DoD) partners with the NNSA in setting requirements and establishing production goals for the stockpile. DoD and the NNSA share responsibility for maintaining the safety and security of the stockpile. The Secretary of Energy is obligated to the U.S. public to ensure that the nuclear arsenal remains safe, secure, and reliable. A key challenge of the SSP is to balance militarily specified weapon performance goals against civilian and military surety[3] concerns.

A significant fraction of the nation's nuclear weapon systems are scheduled to undergo modernization, starting this decade. Two systems, the W80 and the W76 warheads, are a key part of the nation's nuclear deterrent, and the refurbishments of these systems will represent a significant effort to be undertaken during this decade. The W76, as part of the Trident submarine weapon system, plays a particularly important role, as one of the most survivable elements of the U.S. nuclear deterrent. Simultaneously, the NNSA must be able to remanufacture weapon components and perform maintenance on stockpiled weapons to continue to certify them as safe, secure, and reliable as they age in the 21st century. Developing the tools, technologies, and skill-base required to modernize and maintain these systems is a major challenge of the SSP. The cost and schedule of developing these tools and technologies, and the availability of the requisite skills in the NNSA's workforce, are important factors in the life

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1. "Stockpile Stewardship Program 30-Day Review," November 1999.
2. Throughout this report, the term "reliability" means that a given weapon will work as expected, including achieving the militarily specified level of performance.
3. Surety connotes both safety (i.e., that a given weapon will not produce nuclear yield in any anticipated or unanticipated environments) and security (i.e., that nuclear yield by a given weapon may only be achieved when properly authorized).

extension programs (LEPs) of these two weapons.

2.1 The Scientific Approach of the Stockpile Stewardship Program

The highest priority of the SSP is to ensure the operational readiness, safety, and security of the U.S. nuclear weapons stockpile. It is through confidence in the operational readiness, safety, and security of the stockpile that deterrence is achieved. The strategy of the SSP is to sustain this confidence by continually surveying, repairing, and maintaining the weapons, and by annual certifying their safety and reliability, based on the expert judgment of scientists and engineers who possess the required scientific tools and facilities. The principal challenge of the SSP is to meet these goals for the indefinite future, without returning to nuclear testing. The premise of the SSP is that reliability and safety of aged and rebuilt nuclear weapons can be assured by combining engineering science, hydrodynamics, high-energy-density physics and materials science with numerical simulations, the scientific pillars of science-based stockpile stewardship. The program premise can only be met with the most advanced applications of all of these sciences.

Since its inception, the SSP has been based on developing a comprehensive scientific ability to analyze the performance of a given nuclear weapon in its stockpile-to-target sequence (STS), including the details of its nuclear detonation, to establish stockpile confidence. The basis of this analysis begins with knowledge gained during the era of nuclear testing and new weapon development. That knowledge base, however, is insufficient to support maintenance of the safety and reliability of the stockpile indefinitely. The SSP has been designed to fill in gaps in the knowledge required to perform these tasks. SSP will use the relevant test data and science to form the basis of a new generation of weapons simulation codes. The codes incorporate, or access, improved physics databases. They use advanced algorithms, and take advantage of the computing power available on the new Accelerated Strategic Computing Initiative (ASCI) machines. An essential element of this strategy is that advanced simulation software must be tested and validated by relevant experiments.

Such tests or benchmarks can take several forms. First, the software must be validated against data from past nuclear tests. These test measurements generally were integral in nature, and left the designer with free parameters, with which to fit the data. However, archived test data are undergoing re-analysis and, backed by better scientific understanding of the interpretation of past measurements, some of the reliance on that modeling empiricism is being reduced. To develop a more detailed understanding of particular physics or materials science within a nuclear weapon, simulation software is validated against high-energy-density physics, radiographic, subcritical, materials, and engineering experiments. In some cases, these experiments provide basic physics data. In others, the experiments verify specific features of simulation algorithms. In yet others, key weapons issues are tested. In the most complex experiments, the capabilities are tested of the software and the designer of integrating multiple effects to simulate complex integral experiments and predict their outcomes. Also, when validated by the right spectrum of nuclear tests and laboratory experiments, the new software can be used to understand issues that arise in weapon surveillance, as well as to explore new concepts for weapon refurbishment or modernization of weapon surety or performance features.

Given the overall vision of maintaining the stockpile without underground nuclear testing, the SSP must determine more specific requirements for its constituent research programs, as well as criteria by which to assess whether the SSP tools will provide sufficient scientific understanding. This examination must look beyond the current status of the weapons and assess the SSP's capabilities to respond to anticipated problems.

A program has been developed for the weapons physics, materials science, and engineering understanding that is needed for the SSP to succeed in the long term. The program is implemented in the SSP business model (see Appendix C) of Campaigns, Directed Stockpile Work (DSW), and Readiness in Technical Base and Facilities (RTBF). A fundamental requirement for the SSP is that all of the science and engineering used to maintain the safety, security, and reliability of the stockpile – the pillars – should be founded on a healthy program of tests and experiments, as well as on sound theories and validated computer simulations. Thus, facilities that provide high-fidelity tests of high-fidelity representations of stockpile materials, components, and assemblies in realistic environments, with good diagnostics, are central to the SSP. Where high-fidelity weapon configurations and environments are impossible to achieve in the laboratory, such as is the case for many weapons physics conditions, the test and experimental program must be carefully developed to provide essential data and validation evidence from which reasonable inferences about weapon performance can be made. The pillars of the SSP are as follows:

Hydrodynamics. Within the SSP, hydrodynamics experiments are fundamental to understanding the performance of the nuclear warhead. A detailed understanding of hydrodynamics is necessary to describe the process of imploding a weapon primary and obtaining nuclear yield, as well as other aspects of performance, including weapons case dynamics. Knowledge of hydrodynamics will be essential for certification of newly manufactured W88 pits, as well as other weapon system LEPs. Major experimental facilities at the laboratories and at NTS are required to validate the physics in the simulation software. An example is the Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility, which uses x-rays to produce three-dimensional imagery of the implosion of surrogate-material pits.

High-Energy-Density Physics. During the operation of a thermonuclear weapon, temperatures, pressures, radiation fluences (i.e., the integral of neutron and photon flux over time, usually expressed in units of particles per square centimeter), and material compositions and densities exist that do not occur elsewhere on earth. The

HEDP pillar of the SSP focuses on developing and using experimental facilities to access this regime of physics, that begins to apply during the implosion of a nuclear-weapon primary. This physics applies from that time on, and is required to understand and validate models of nuclear weapon performance. These facilities also provide data that are important to modeling primaries. The radiation environments created by some of these facilities also are be used to simulate some of the environments to which a U.S. warhead would be exposed if it encountered a nuclear blast in its STS environment. These nuclear-weapons effects tests enable designers to optimize the survivability of weapons in projected threat situations. Examples of HEDP experimental facilities include NIF, Omega, and the Z accelerator. A more complete description of the NNSA HEDP facilities is contained in Appendix D.

Materials Science. The third pillar of the SSP focuses on providing comprehensive scientific understanding of weapon materials and how they respond in STS environments, particularly with respect to aging. A significant goal in this area is the ability to predict materials aging problems and correct them before they can impair a weapon's safety or reliability. Materials science experiments are conducted at a wide range of facilities, including some HEDP facilities. This is particularly challenging for nuclear weapons, because they use materials that are not used extensively elsewhere. Examples include plutonium, a man-made element, and insensitive high explosives. Because of the ionizing radiation from the fissile material in nuclear weapons, weapon materials are subject to environments that are not experienced elsewhere, even in nuclear reactors.

Engineering Science. Within the SSP, this pillar embodies the understanding required to assess and certify the myriad parts of a weapon, in addition to the primary and secondary. Examples of nonnuclear components include neutron generators, fuzes, timers, and batteries. A modern nuclear weapon includes more than a dozen subsystems and as many as 5,000 individual parts. Engineering science provides the tools and knowledge to integrate them into a reliable, safe nuclear weapon that can be certified. This pillar is facility intensive, because it requires the ability to produce radiation-hardened microelectronics and to conduct experimental tests of individual parts, components, and subsystems.

Advanced Simulation and Computing. Advanced simulation and computing techniques integrate all the knowledge generated by the science pillars and provide a high-fidelity, predictive understanding of a weapon in all environments. Development of these techniques involves, in partnership with U.S. computer manufacturers, the world's most powerful computers (currently capable of performing ~5 trillion[4] operations per second), computer algorithms based on validated high-fidelity physics, three-dimensional models, capable of simultaneously

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[4] See www.top500.org.

applying 10,000 individual processing elements in a single simulation, and the application of these tools to predict the behavior of nuclear weapons.

2.2 Deliverables and Outcomes of the SSP

As described in Section 2.1, the most important outcome of the SSP is sustained confidence in the operational readiness, safety, and security of the U.S. nuclear weapons stockpile. Another significant outcome is demonstrating to foes and allies that the U.S. has the resolve to possess and exercise the scientific and technical means required to sustain that confidence, indefinitely, without nuclear testing. This includes having the skilled stockpile stewards and developing the tools they need to assess and resolve problems in the stockpile; retaining the capability to produce new weapon designs, if necessary; and having the manufacturing infrastructure necessary to survey, maintain, and modernize existing weapons, as well as to fabricate new components, subsystems, and weapons in the future, as necessary.

2.2.1 ANNUAL ASSESSMENT AND CERTIFICATION OF THE STOCKPILE

By presidential directive, the Secretaries of Defense and Energy are required to certify annually to the President whether or not a return to underground nuclear testing has become necessary to retain confidence in the performance and safety of the weapons in the U.S. nuclear weapons stockpile. To date, five such certifications have been made, and a sixth is in process.

During the HEDP Workshop, the three NNSA national laboratories presented their respective approaches for this annual certification of the stockpile. These approaches, while differing in detail, are complementary and have arisen out of the differing responsibilities and perspectives of the laboratories in the development of nuclear warheads. The fact that the laboratories have somewhat differing approaches provides diversity that can lead to more overall confidence in conclusions drawn about U.S. weapon systems safety and performance. This section summarizes the three approaches.

Los Alamos National Laboratory (LANL) Approach to Certification. LANL's current approach to certification relies largely on "*equivalency*." The first principle of equivalency is to maintain the weapon's physics and engineering design package, as well as the materials and processes used to produce and manufacture components, as close as possible to the as-designed, as-built, and as-tested conditions that existed when the weapon was certified by nuclear tests. The second principle of equivalency is to make only engineering changes that remain near or within regimes that have been nuclear-tested. LANL's certification activities rely heavily on designer judgment, surveillance, simulation, an aggressive hydrodynamics test program, an extensive materials science program, and support from a diverse suite of experimental and computational facilities. Maintaining these activities in balance is key to current and future certifications. Among the balanced portfolio of activities is a strong HEDP Program.

While not immediately available for upcoming SSP activities, LANL believes that NIF, as its beams are commissioned, will become an important source of weapons physics data. The certification process will evolve, taking advantage of modern tools, as they become available.

Lawrence Livermore National Laboratory (LLNL). Approach to Certification. LLNL's process for certification involves two major steps. The first is to identify all significant potential failure modes by using scientific and engineering judgment, results from past nuclear tests, aboveground tests and experiments, surveillance, and advanced computational simulations. Second, LLNL scientists and engineers pursue a program to quantify the margin and the associated uncertainty, to the extent possible, for each potential failure mode. Certification is achieved by demonstrating that the margin in performance is greater than the uncertainty in the performance prediction for each potential failure mode of the device. A key premise of the LLNL approach is the conceptualization and development of scientific and computational tools to explore all weapon-relevant physical regimes. High-energy-density physics at NIF is key to a successful LLNL certification program and to increasing certification confidence in the future.

Sandia National Laboratories (SNL) Approach to Certification. SNL is responsible for the nonnuclear subsystems of nuclear weapons and overall weapon-system integration. All SNL-accountable weapon components and subsystems can be tested experimentally, except under conditions of heat, blast, and radiation that could be encountered by a given weapon were it exposed to a nuclear blast in its STS environment. HEDP facilities provide important aboveground test environments for nonnuclear components in such hostile environments. SNL develops and qualifies its components and subsystems for certification by identifying uncertainties in performance and safety, using scientific and engineering judgment, and the results from past nuclear tests, aboveground tests, experiments, and simulations. Components and subsystems are then tested, analyzed, and simulated to reduce uncertainties in performance and safety. Where possible, environments as close as possible to those anticipated in nuclear threat conditions are simulated experimentally, using nuclear reactors and pulsed-power accelerators. SNL, in conjunction with the LANL, LLNL, and DoD, also conducts flight tests of warheads that have been modified by replacing the nuclear explosive package with instrumentation and telemetry that sense the operation of different aspects of a weapon and transmit those data back to the laboratory for analysis to verify correct function or to identify and assess potential problems. This type of testing is the closest possible to conducting full-systems testing of a nuclear weapon.

2.2.2 RECRUITING AND RETAINING CRITICALLY SKILLED PERSONNEL INTO THE STOCKPILE STEWARDSHIP PROGRAM

To be successful, the SSP requires a balanced program with state-of-the-art tools and facilities, and also a community of experts with well-developed judgment in areas of science and engineering related to nuclear weapons performance and safety. Developing both the tools and the cadre of experts with requisite knowledge and judgment requires a substantial, sustained investment.

The SSP faces a significant conundrum. To sustain confidence over the long term, the best possible scientists and engineers must be available. However, many of the scientists and engineers at the NNSA national laboratories, production plants, and test site are approaching retirement age. A recent analysis[5] found that the average age of critically skilled nuclear weapons workers across the weapons complex is 47 years and that 61 percent of all critically skilled workers will be eligible to retire before 2010. The data for laboratory personnel who have served as lead designer on actual underground nuclear tests are even more startling, with nearly all such persons being eligible to retire by 2004. To attract and retain the replacement workers for the next generation of stewardship, stimulating scientific and engineering work must be available in the Nuclear Weapons Complex.

Two factors that will help attract and train new staff are having challenging work that is of recognized national importance and having scientific tools that are unavailable elsewhere. This new stewardship paradigm replaces the weapon development paradigm that ended September 27, 1991, when President George H. W. Bush cancelled new warhead designs that were in process. Between then and now, the earth-penetrating B61-11 was developed and produced to replace the aging B53, and the W87 LEP refurbishment began in 1999. Both involved significant development activities. These refurbishment programs posed substantial schedule-driven design challenges for the weapons laboratories. Recently, the authorizations by the Nuclear Weapons Council to begin development programs to refurbish the B61-7/11 bomb and the W76 and W80 warheads have led to new design activities. To a large extent, these programs have helped to revitalize the weapons design and engineering communities, while tasking experimental programs to resolve individual details of nuclear weapons phenomena that were previously measured in nuclear tests. While the weapons refurbishments seem to be revitalizing the existing design and engineering community, they have not favorably affected the laboratories recruiting efforts.

Within the SSP, scientific areas that have major recruitment appeal include Advanced Simulation and Computing (ASC), the materials program, and HEDP. Through these programs, members of the nuclear weapons laboratories collaborate with university faculty, and students participate in activities that contribute to maintaining the U.S. nuclear deterrent. While the details of weapons phenomena relating to a specific warhead are sensitive and classified, a significant amount of the

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[5] "Nuclear Skills Retention Measures within the Department of Defense and the Department of Energy," November 2000.

science underlying prediction of these phenomena are not. Joint laboratory and university participation in publishable, unclassified research leads to many benefits: 1) they strengthen the scientific understanding used to predict nuclear-weapons performance, 2) they develop a community from which the nuclear weapons laboratories can recruit, and 3) they allow peer review of the caliber of science and scientists that constitute the U.S. nuclear weapons program. The combination of heightened activity in stockpile refurbishments and vital research programs in the SSP, including university outreach, provides a basis for recruiting and retaining critically skilled personnel.

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CHAPTER 3

Overview of the Baseline High-Energy-Density Physics Program

Overview of the Baseline High-Energy-Density Physics Program

This Chapter summarizes the baseline HEDP Program, including its mission, program elements, requirements that stem from the SSP, goals, and international collaborations. Also included is a synopsis of reviews of the HEDP Program since 1990.

3.1 Mission of the High-Energy-Density Physics Program

The mission of the HEDP Program is to provide high-energy-density (HED) physics data and scientific understanding to maintain the safety, security, and reliability of the nation's nuclear weapons, now and into the future, without nuclear testing. The HEDP Program, in areas such as demonstrating fusion ignition, studying the feasibility of high-yield fusion in the laboratory, and advancing basic scientific understanding, also supports broader, national research objectives in areas, such as fusion energy.

3.2 Program Elements and Participation

All three NNSA national laboratories, as well as the University of Rochester's Laboratory for Laser Energetics (UR/LLE), the Naval Research Laboratory (NRL), a number of universities, and other institutions, collaborate in the research activities of the HEDP Program. Included within the Program are facility and related technology development, experimental science, theoretical science, materials science and computational model development. Chief among the activities in the HEDP Program is the conduct of experiments to illuminate and resolve specific high-energy-density physics uncertainties. The majority of these experiments is designed and fielded by scientists in the nuclear weapons programs at the NNSA national laboratories. State-of-the-art diagnostics and precisely manufactured target test articles, developed at all HEDP research institutions, underpin these experiments.

Today, there are seven principal HEDP facilities spanning both laser and pulsed-power capabilities, including Omega at UR/LLE, Z and Saturn at SNL, Trident at LANL, Nike at NRL, Atlas, which is being moved from LANL to NTS, Janus at LLNL, and NIF, presently under construction at LLNL. A second HEDP construction project is the Z-backlighter, expected to be complete in FY 2002. The HEDP Program supports a full target physics base program at the University of Rochester and the NRL, in addition to the Omega and Nike facilities. Target development and production is concentrated at General Atomics (GA), Incorporated, in La Jolla, California.

The current NIF Project baseline was approved by the Secretary of Energy on September 15, 2000. It includes both construction and operating funds through FY 2008. Within the baseline HEDP Program supporting NIF, but not included in the NIF Project, there are diagnostics and cryogenics required to support weapons physics and ignition goals. Based on nearly thirty years of laser development for fusion, NIF is designed to deliver 1.8 megajoules (MJ) of energy, with 50-micrometer precision, onto millimeter-size targets. The intent is to produce thermonuclear burn that, for a few trillionths of a second, produces some of the conditions found only in the center of stars and in the core of an exploding nuclear weapon. Achieving this ignition outside of a nuclear device will be a landmark achievement for the SSP. Independent of achieving ignition, NIF will increase the nuclear-weapons-physics parameter space presently available to scientists, as compared to facilities that exist today.

Within DP's SSP business structure of DSW, Campaigns, and RTBF, the HEDP program consists of a mix of activities drawn from many of these elements. DSW utilizes HEDP facilities to support its work, and RTBF provides some support for its facilities. The HEDP Program has activities in Primary Certification, Dynamic Materials Properties, Secondary Certification and Nuclear System Margins, Hostile Environments (Nuclear Survivability), Inertial Confinement Fusion (ICF) Ignition and High Yield (consists of the ICF technical program for ignition, stockpile support, and high yield, NIF and pulsed-power technology development, and operations of existing facilities), and the ASC Campaigns. For purposes of this study, however, ASC-funded HEDP activities are not considered in detail. The validation of ASC computer codes via experiments using HEDP facilities is included in this study, as is the total scope of computational activities within the ICF Program.

The ICF Grants Program supports basic HEDP science within and external to the DP laboratories. The current grants program funds twenty-two HEDP researchers at universities and other institutions. University researchers presently utilize the Omega laser, Z, and Trident.

3.3 Program Requirements

For the SSP to be successful, that new experimental and computational capabilities must be developed to address the technical challenges associated with a science-based understanding of all aspects of nuclear weapons in the stockpile, from storage in the stockpile to delivery on target. LEPs in the coming decade, as well as findings from the ongoing stockpile surveillance program, will raise questions related to the high-energy-density regime that must be answered to continue certifying current stockpile weapons. To answer these questions, the HEDP Program must provide the scientific understanding and experimental capabilities to validate simulation software, including diagnostics. The program must also collect fundamental information for databases. The HEDP Program may also develop advanced radiation sources, includinghigh-yield sources, for nuclear effects testing. Finally, to serve its mission in the advancement of basic fusion-energy science, the program provides facility time and access to the broader scientific community.

Specific physics regimes for HEDP experiments have been identified in the following areas:

- High-temperature opacity of weapon materials,
- Materials studies, including high-pressure equation-of-state (EOS) experiments of weapon-relevant materials in the HED regime,
- Radiation experiments pertinent to the weapons regime,
- Complex, compressible hydrodynamic experiments, involving, for example, engineering features, such as gaps or grooves, and
- Thermonuclear deuterium-tritium (DT)-ignition experiments.

More detailed requirements for the HEDP Program, specifying the physical regimes of interest in these areas, are contained in the SSP "Criteria Report."[6]

3.4 Goals of the High-Energy-Density Physics Program

From the HEDP mission and requirements, a set of high-level goals has been derived, on which the national program focuses. Maintaining breadth in the HEDP Program, defined by these goals, is essential to meeting the goals of the SSP. The diversity in the goals has allowed a substantial HEDP community to develop during the past thirty years. While the requirements for HEDP and the overarching philosophy behind the HEDP Program have remained the same since the nuclear testing moratorium began in 1992, advances in HEDP research and development have encouraged the evolution and fine tuning of the goals. These goals lay out the breadth of the Program's research for this decade.

The program of activity in HEDP is constructed around national strategies to reach these goals. The overall program strategy is to ensure, in conjunction with the laboratories, other federal agencies, and other participating institutions, that the national scientific base in HEDP is adequate to support both short- and long-term goals of the SSP. These individual strategies exercise and build HEDP expertise across the nation, first and foremost at the weapons laboratories, but also at universities and other institutions. The success of each is largely dependent on the effective teaming among the workforce at these institutions and on stable support for the HEDP activities from NNSA.

The goals of the HEDP Program and the national strategies presently defined by DP are as follows:

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[6] *Report on Criteria for Stockpile Stewardship Tools* (classified Secret/Restricted Data), prepared by the U.S. Department of Energy, in response to Section 3158 of the National Defense Authorization Act for Fiscal Year 1999 (P.L. 105-261), May 14, 2000.

3.4.1 EXECUTE HIGH-ENERGY-DENSITY WEAPONS PHYSICS EXPERIMENTS REQUIRED BY THE SSP FOR ENSURING THE PERFORMANCE AND SAFETY OF THE NUCLEAR STOCKPILE.

As noted elsewhere in this report, significant stockpile actions have been accomplished since the inception of the SSP, and several major stockpile actions are in planning and development stages. Successful execution of these stockpile actions, resolution of findings in the surveillance program, and preparation for future issues in the stockpile, require a robust weapons assessment and certification program, as well as the manufacturing capability to refurbish weapons. Stockpile assessments and actions already accomplished have utilized the most advanced HEDP experimental capabilities and computational tools available for confident resolution of weapon performance issues. As weapons age, and further actions are required, more advanced tools will be required to sustain confidence in the safety and reliability of the stockpile.

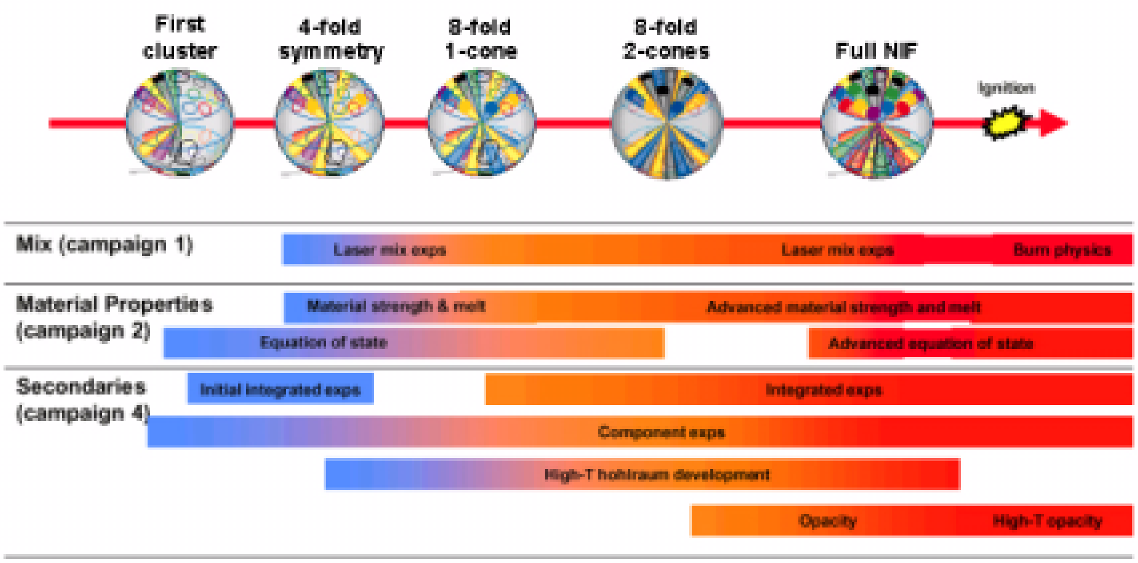

Figure 3-1. A national program has been developed to use NIF to investigate a series of weapons-related phenomena.

HEDP experiments are required to address weapons physics issues, acquire basic physics data and validate codes, and develop the expertise and judgment necessary to assess and certify nuclear weapons performance and safety. A core activity of the SSP is to develop modern computational baseline models for each weapon type. These baselines begin with the archived knowledge of the original weapon design and its tested performance. As the weapons age, understanding the details of weapons performance, materials in weapons, and weapons phenomena and incorporating that understanding into modern computational simulation tools has become critical. One of the fundamental goals of the HEDP Program is to provide the scientific understanding and physical data, in the high-energy-density regime to build and validate the new baseline models. This understanding is developed through an integrated program of past nuclear test data, weapons physics experiments, computational model development, and fundamental theory.

The energy densities produced at HEDP facilities are the highest attained in the laboratory. NIF should produce conditions that can be used to explore scaled phenomena that are similar to those that occur in nuclear weapons, albeit on a microscopic scale. These include complex hydrodynamic experiments to study flows under extreme conditions and for instabilities that occur at material interfaces, radiation flow experiments to assess the transfer of energy by radiation in materials, and experiments to measure the properties of materials, such as equations of state and opacities. Additionally, a host of integrated physics experiments will simultaneously test simulation-software capabilities in the area of coupling radiation and hydrodynamics.

Ignition experiments at NIF have the potential to extend these weapons physics experiments to study issues relevant to the thermonuclear burn process. These include the minimum requirements for ignition and the effect of implosion asymmetry and hydrodynamic instability on ignition. Experiments using direct-drive targets (see Section 3.4.2) may achieve higher gains than those using indirect-drive targets, and will likely be preferable for studying more marginal systems. The use of laser beams or pulsed-power devices to produce a field of high-energy x-rays inside a hohlraum provides a uniform high-energy illumination capability that can uniquely probe indirect-drive fusion ignition and other weapons-physics phenomena, such as those discussed above.

The HEDP experimental suite for weapons physics includes complementary activities at pulsed-power and laser-driven facilities. HEDP experiments presently are performed at the Omega, Z, Trident, Janus, Nike, and Atlas, and Saturn facilities. When NIF becomes operational, it will be central to providing the HEDP knowledge required to assessing and certifying the stockpile. Approximately 45 percent of the experiments at NIF will be devoted to weapons physics, beginning in the FY 2006-2010 timeframe, with the balance focused on experiments on ignition, high yield, weapons effects, and basic science. The DP strategy for meeting weapons-physics requirements would be significantly undermined without NIF.

3.4.2 DEMONSTRATE IGNITION AT NIF BY 2010.

Demonstrating thermonuclear ignition in the laboratory is a major goal of the ICF Program within the HEDP Program. It is the next step in the application of HEDP to weapons issues and in application of ICF to a wider range of defense and energy applications. After ignition is achieved, many specific weapons physics issues related to fusion burn can be addressed.

There are two different approaches to achieve ICF ignition. One, referred to as direct drive, involves a spherical target containing the fuel that is struck directly by a laser or other type of driver beam.

The other, referred to as indirect drive, involves a fuel capsule that is mounted inside a thin-walled, high-density material cylinder, such as gold. In laser indirect drive, the laser beams are aimed through the holes at each end of the cylinder, such that they strike the inside walls of the cylinder, where their energy is converted to x-rays, which then strike the fusion capsule. The pulsed-power approach uses the x-rays produced by an imploding z-pinch plasma to created the x-rays that drive the fusion capsule. In both direct and indirect drive, the energy absorbed by the fuel capsule causes it to implode, bringing it to the necessary temperature and pressure for fusion to occur. The first attempts to achieve ignition on NIF will use the indirect drive approach.

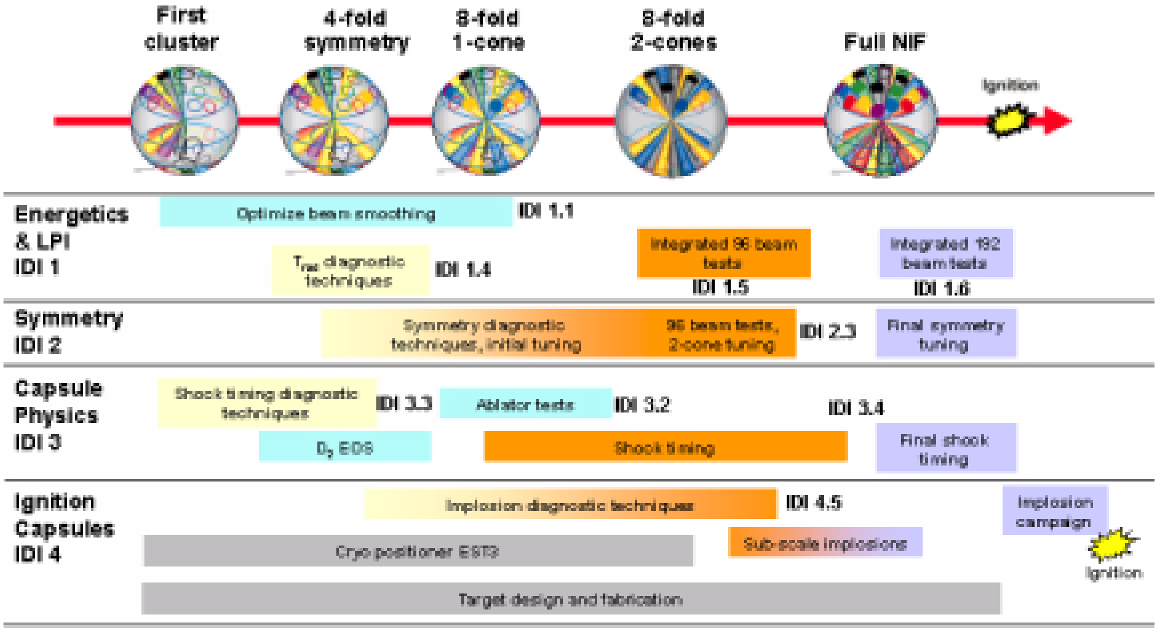

Figure 3-2. A national program outlining the series of experiments needed to assure a successful demonstration of ignition at NIF by 2010 utilizes NIF at all beam configurations.

Numerous reviews of the ICF program (described in Section 3.6) have affirmed that 1.8-MJ energy, delivered in a highly tuned pulse, to an indirect-drive ICF target, held at cryogenic temperatures, should be adequate to ignite deuterium-tritium fuel contained in the target capsule. NIF was designed to provide these conditions.

Demonstrating ignition in the laboratory is a grand, scientific challenge that has eluded solution for years. The ICF Program has attracted, and continues to attract and develop, the best and brightest HEDP scientists in the country. The challenges posed by the goal of achieving ignition serve to promote research in numerous fields, such as advanced high-power laser physics, optical engineering, advanced pulsed-power technology, materials science, radiation transport, hydrodynamics, plasma physics, atomic physics, and engineering. Setting the goal of achieving ignition by the end of this decade allows the ICF Program to continue its momentum, demanding top performance by all HEDP scientists in a number of key research fields. Ignition will be a highly visible, exciting landmark accomplishment for DP. Achievement of ignition at NIF also serves the broader national interest in contributing to the fusion-energy mission of the Department of Energy's (DOE) Office of Fusion Energy Science (OFES).

The study of ignition and ignition-related phenomena will serve to develop a better understanding of a number of weapons phenomena. Foremost, achievement of ignition will allow the program to study thermonuclear burn in the laboratory. Also important is that the achievement of ignition will require an integration of complex physics and engineering, on a level of difficulty comparable to that involved in the successful test of a nuclear device. This will provide an important proving ground for both advanced weapons codes and models, and for designers, who will be responsible for making assessments regarding the safety and reliability of nuclear weapons.

The strategy for achieving ignition follows that outlined in the 1990 National Academy of Sciences (NAS) study, and is detailed in the ICF Campaign Program Plan and the NIF Facility Use Plan.[7] Indirect drive, which has been thoroughly researched on Nova, Omega, and Z will be the first technique used in the attempt to achieve ignition. Over time, the HEDP Program will pursue both direct- and indirect-drive ignition. For indirect drive, physics readiness has been validated via completion of a program of experiments, including those under the Nova Technical Contract.[8] Experiments are ongoing at Omega, Trident, Nike, and Z, providing contributions to achieving ignition. The effort to further direct-drive technology for an ignition demonstration is conducted at the Omega facility through a multi-laboratory collaboration. To reduce the risk and cost of the effort, international collaborations with Commissariat à l'Énergie Atomique (CEA) and the United Kingdom (UK) are ongoing, and remain an important element of the strategy. Approximately 45 percent of the planned experiments at NIF will focus on achieving ignition.

3.4.3 ATTRACT, TRAIN, AND RETAIN OUTSTANDING TALENT TO THE HEDP PROGRAM AND THE SSP.

One of the foremost goals of the HEDP Program is training U.S. scientists in the fields of stockpile stewardship, nuclear weapon design, and in the pillars, including HEDP. The day-to-day challenges of maintaining the nuclear

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[7] Facility Use Plan of the National Ignition Facility, Edition 1, draft prepared for the Office of Inertial Fusion and the National Ignition Facility Project, Office of Defense Programs, U.S. Department of Energy, April 1997 (LALP-97-7, UC-700).

[8] Second Review of the Department of Energy's Inertial Confinement Fusion Program Final Report, National Academy of Sciences, September 1990.

stockpile require a highly talented workforce at the DP national laboratories. For the U.S. to maintain a credible nuclear deterrent into the indefinite future requires the U.S. to maintain a core community of the best and brightest HEDP scientists.

The strategy to accomplish this goal involves moving forward with developing state-of-the-art experimental and computational facilities. Among these is demonstration of ignition demonstration at NIF and supporting the diverse capabilities in the U.S., on which to investigate aspects of HEDP science. Maintaining a critical mass of HEDP experts at the NNSA national laboratories is key to maintaining the nuclear stockpile. Engaging a larger community of experts at institutions across the U.S. serves to maintain the nuclear deterrent for the longer term.

The quest for ignition has attracted, and continues to attract and engage, a wide variety of both young and senior scientists at a number of institutions. The ignition program is largely unclassified, allowing for peer review, publishing, and development of cross-institutional collaborations. The fact that the ignition program is international adds to the attraction for many individuals. There is concurrence[9,10] that NIF will be among the most significant critical-skills personnel “attracters” in the SSP. The HEDP Program is an important point of entry to the NNSA national laboratories for highly skilled scientists, who often become engaged directly in the nuclear weapons program.

Meeting the challenge of ignition will require technical development in HEDP and supporting technologies. Pursuit of this research will serve to train scientists and engineers, while advancing science and technology in areas overlapping and parallel to nuclear weapons program activities. The stresses of striving for ignition by 2010 will lead to increased collaboration and peer review, tuning and refining the knowledge and talents of those involved in the ignition goal.

There are a number of other technical goals within the HEDP Program, including those associated with weapons effects and high yield. They also capture the imagination and harness the creativity of scientist and engineers analogous to the pursuit of ignition at NIF, as well as providing valuable recruitment opportunities.

3.4.4 COMPLETE CONSTRUCTION OF THE NIF PROJECT AND THE Z-BACKLIGHTER ON THE CURRENT COST AND SCHEDULE BASELINE.

NNSA currently has two construction projects in progress to support the HEDP Program, NIF and Z-backlighter.

NIF is a 192-beam, nyodimium-glass laser system under construction at LLNL. DOE initially authorized the NIF Project in 1994. In September 2000, the Secretary of Energy approved a

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[9] Review of Science Based Stockpile Stewardship, JASON Committee, November, 1994 (JSR-94-345).

[10] Inertial Confinement Fusion Review, JASON Committee, March 1996 (JSR-94-300).

new project baseline, because of cost and schedule issues. The present NIF baseline schedule is shown in Figure 3-3, with completion of all 192 beams in FY 2008. NIF is being built modularly, with increasing numbers of beams available for experiments, at dates intermediate to FY 2008. The NIF deployment strategy is provide in Appendix E.

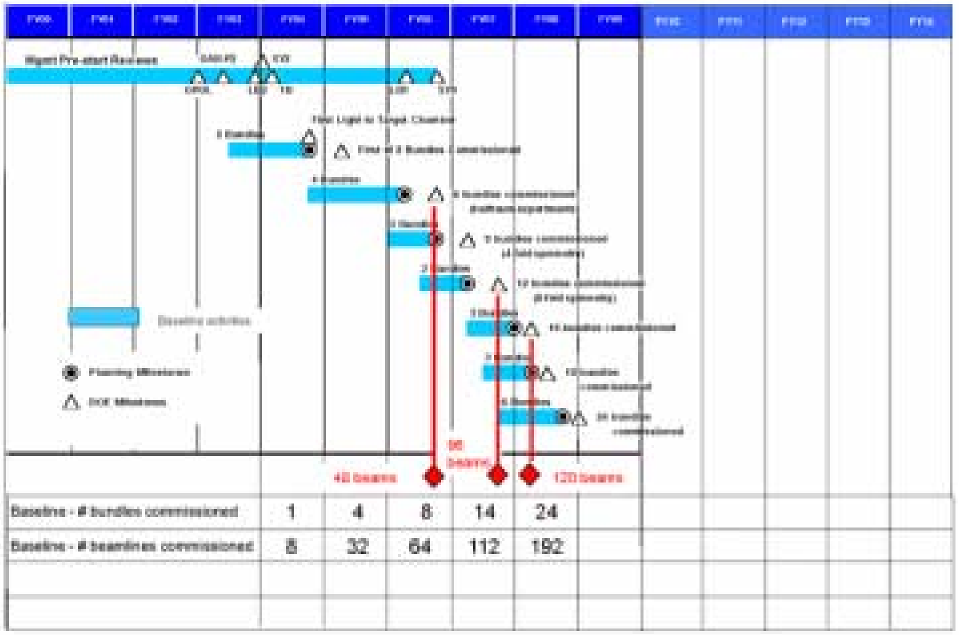

Figure 3-3. The approved baseline schedule for the availability of beams at NIF.

The Z-backlighter is a Nd-glass laser being installed on the Z machine at SNL. The laser will be used for x-ray backlighting, synchronized to Z-pinch implosion, producing x-ray radiography and probing of Z experiments, such as the study of hydrodynamics, materials properties, and inertial confinement implosions. The Beamlet laser, used to test the NIF laser design at LLNL, has been moved to SNL to be used to implement the Z-backlighter. The Z-backlighter project began in 1999 and will be completed in FY 2001.

3.4.5 DEVELOP AND FABRICATE THE CRYOGENIC SYSTEMS AND DIAGNOSTICS REQUIRED FOR NIF.

Of the significant technology developments required for weapons physics and ignition experiments on NIF, two key areas are diagnostics and cryogenic targets. There has been substantial work performed and is ongoing in the present baseline HEDP Program in these two areas. In fact, the systems needed for NIF have largely evolved from systems fielded at other HEDP facilities.

All experiments at NIF require a substantial array of sophisticated x-ray, optical, and neutron diagnostics to measure the conditions in targets irradiated by the laser. Having such an array of high-resolution, time-gated, very fast diagnostics available increases the utility of each experiment, by diagnosing all aspects of target performance. This detailed diagnosis of each HEDP target at NIF feeds directly into validation of computer simulations of target behavior.

NIF diagnostics have been divided into two groups, Phase 1 or core diagnostics and Phase 2 diagnostics. The core diagnostics are the standard suite of HEDP x-ray, neutron, and optical instruments used to measure target and laser performance. These require minimal or no development to deliver operational systems to NIF. The Phase 2 diagnostics are generally specific to an individual user or particular application and usually require significant development. To assure appropriate project management, DOE/NNSA will "projectize" the NIF core diagnostics within the HEDP Program, because they are not funded in the NIF Project. Initially, the scope of the diagnostics project will be the delivery of the core (phase 1) diagnostics as presently defined. As diagnostic needs are reviewed, the core list may be changed as appropriate. Although NNSA national laboratories have lead responsibility for the majority of the diagnostic development activities, the HEDP Program includes participants from other laboratories.

Achieving ignition at NIF and obtaining a wide range of weapons physics data are dependent on more factors than laser performance. All of the principal ignition target candidates make use of a frozen-fuel layer in the target capsule. This ultra-smooth surface, cryogenically frozen deuterium-tritium fuel layer, is critical for obtaining appropriate shock compression of fuel to the high densities required for thermonuclear hot-spot ignition.

Advances in producing cryogenic fuel layers have been made by teams of scientists working at LANL, LLNL, and GA. Direct-drive target experiments at UR/LLE have tested this technology, enhancing its practical implementation at NIF. In its program and implementation plans, the ICF Program has defined the work required for obtaining the necessary cryogenic layers and characterizing these layers for ignition experiments at NIF. A plan describing the activities required to produce ignition targets is in preparation.

In addition to ignition targets themselves, a cryogenic system is required to hold the target in the chamber and prepare it for laser irradiation. The importance of this system has led NNSA to “projectize” this activity, to ensure that the cryogenic system will be available in the correct timeframe for NIF ignition experiments.

The NIF cryogenics target systems project includes developments needed for an indirect-drive ignition demonstration at NIF. The system has been designed to be consistent with the requirements of direct-drive targets, so as not to preclude the fielding of direct-drive targets on NIF. Further development and construction will be necessary before cryogenic direct drive ignition targets can be fielded. The NIF cryogenic target systems project will include the cryogenic ignition target manipulator, the target insertion cryostat, a Mark I target manipulator, if necessary (to be used for pre-ignition experiments in simplified geometries), and the cryogenic target fill systems and supporting infrastructure. The project also includes cryogenic systems engineering and technology development required for project completion, as well as interactions with the French CEA for cryogenic systems development. Additionally, the project is to be integrated with, but does not include, target filling facilities.

3.4.6 DEVELOP ADVANCED X-RAY SOURCES FOR NUCLEAR WEAPONS EFFECTS TESTING.

A key goal of the HEDP Program is to provide x-ray sources for nuclear weapons effects testing, which is necessary in weapons certification, and to continue developing advanced x-ray sources. Nuclear weapons must be capable of operating in a wide range of severe environments, including heat, blast, and radiation from nearby detonation of a nuclear device. Whenever possible, weapon performance is qualified by testing hardware in high-fidelity radiation environments produced in the laboratory. A high-fidelity environment matches the important characteristics of a given threat that drive damage mechanisms in the hardware to be qualified. Many threat environments can be simulated with high fidelity in the laboratory, using pulsed-power and fast-burst reactor technologies. With existing facilities, it is possible to generate high-fidelity neutron and gamma environments and some high-fidelity hot x-ray environments. To date, it has not been possible to perform high-fidelity laboratory simulations of cold or warm x-ray environments. While past underground nuclear effects tests were far from perfect, they generated cold and warm x-ray environments of much better fidelity than is available in the laboratory today. When it is not possible to reproduce the essential features of a threat environment, computer simulations are relied upon to provide radiation response data. In this case, experimental facilities are required to measure materials properties and to help develop models of phenomena needed for these calculations. Experiments also validate the ability to calculate radiation responses. NIF, or any new facility, could potentially impact the qualification of hardware in hostile environments, either by providing a high-fidelity environment that would not otherwise exist, or by providing additional experimental capabilities to develop and validate computational tools.

Weapons are qualified in cold x-ray environments using two basic steps. First, data taken from experiments, in which coupons of reentry body materials are exposed to x-rays, are used to derive impulse models. Second, the impulse models are used either to set up a full-system impulse experiment (e.g., using a magnetic flyer or light-initiated, high-explosive facility), or to develop a computer simulation of the reentry body response. This strategy has not changed significantly in decades, except that in the past, underground nuclear tests were used to generate data on coupons. System-level cold x-ray tests on reentry bodies were almost never performed in underground nuclear tests. In the future, intense laboratory x-ray sources that may perform coupon experiments will be used, as new materials are introduced into the stockpile that have not been tested underground. Today, z-pinch sources on Saturn and Z are used to develop impulse models. NIF is a potential alternative to z-pinch sources for coupon experiments, but it appears that its x-ray fluences will be approximately the same as existing sources.

In the past, most underground nuclear effects tests were performed to address warm x-ray issues. With the cessation of nuclear testing, the current strategy has several elements. Coupon experiments, using laboratory radiation sources, provide materials properties that are used to calculate the response of weapon components. For each area of concern, experimental techniques must be developed to determine damage thresholds or place lower bounds on these thresholds. The design margin is determined by comparing the damage threshold with the calculated response of a component in a threat environment. These response calculations must be validated experimentally. This approach faces significant challenges and is not without technical risk. NIF is a potential alternative to z-pinch sources for validating the ability to calculate component responses. If NIF sources can be developed that are more efficient at producing x rays above ~10 keV than z-pinches, they may offer unique advantages in studying certain effects, such as cavity system-generated electromagnetic pulse (SGEMP). However, neither NIF nor presently contemplated z-pinch sources will provide high-fidelity, warm x-ray environments for system or component certification.

In support of the use of NIF for effects testing, at the request of the Defense Threat Reduction Agency (DTRA), a number of enhancements and modifications to the NIF facility have been implemented. These include three large target chamber ports to allow placement of test objects up to 3 meters in length, 1 meter in diameter and 15 tons in weight. Joint work between LLNL and the Defense Threat Reduction Agency (DTRA) has developed designs to direct NIF beams to the corners of a 5-cm × 5-cm square (and to a 50 cm x 50 cm square with dedicated final optics). Increased flexibility in beam steering and focusing for all wavelengths is being designed into NIF in order that a variety of target arrays can be fielded using all of NIF's 192 beams to achieve large area fluences of x-rays with tunable energy and timing.

In summary, the HEDP Program offers access to some of the conditions necessary for nuclear weapons effects testing through its x-ray source facilities. The Nuclear Survivability (formerly Hostile Environments) and ICF Campaigns support efforts in x-ray source development for nuclear weapons effects testing. The bulk of this work occurs on pulsed-power machines, including Saturn and Z. During the past five to eight years, there has been an examination of the use of lasers in this area. Currently, a small fraction (fewer than 10 percent) of the shots planned at NIF are allocated to this testing.

3.4.7 DEVELOPING OPTIONS, IN THE 2008-2010 TIMEFRAME, FOR A NEXT-GENERATION, HIGH-YIELD FACILITY.

The goal of the present high-yield effort is to provide the nation with a development path for high yield in the 2008-2010 time frame, should the nation decide to take this step. A decision by the U.S. to build a high yield machine could involve considerations beyond DP. The high-yield program developed around this requirement may also provide access to unique weapons physics environments, particularly for weapons-effects experiments that require x-rays with energies of 10-100 keV, and could enable advanced thermonuclear burn related experiments. The strategy involves performing a set of activities, as outlined in the DP ICF technical research contract for high yield z-pinch physics. The NIF ignition demonstration and pulsed-power physics readiness assessment will provide inputs for a potential decision to pursue high yield at NIF.

The majority of the ICF-Program-supported research toward the high-yield assessment for pulsed power is conducted on Z, in partnership with other institutions. There also is substantial effort at LLNL directed at achieving high yield with the NIF system. There are also advanced concepts for laser ignition being pursued outside of the national laboratories, such as the "fast-igniter" concept, which uses very-high-power, short-pulse lasers. This research is funded through the OFES, ICF, and HEDP Grants Program.

The pursuit of high yield is a significant and exciting challenge, analogous to the pursuit of ignition. It serves the same role of attracting and energizing top talent in the program. Development of technologies for a high-yield facility parallels the activities in the inertial fusion energy community.

3.4.8 DEVELOP THE ADVANCED LASER AND PULSED-POWER TECHNOLOGIES REQUIRED FOR NIF AND A POTENTIAL NEXT GENERATION PULSED-POWER MACHINE, RESPECTIVELY.

The HEDP Program maintains an active program in laser and pulsed-power technology development to continue its ability to successfully develop world-class facilities. These facilities include NIF, presently under construction, and a potential next-generation pulsed-power machine. The technology development also benefits existing facilities, such as Omega and Z, by allowing incremental improvement in performance.

Before NIF construction began, significant advances were made in large-aperture pulse switching, multipass amplifier development, high-efficiency amplifier design, laser modeling, and materials developments, enabling NIF to be designed more efficiently than previous lasers. More recently, advances have been made in clean assembly, potassium dihydrogen phosphate (KDP) crystal growth, and handling laser damage to the glass that are important in meeting NIF performance specifications. LLNL has demonstrated most of the individual technologies needed for NIF to meet its baseline function. As NIF is built, issues are anticipated to arise that will require a robust laser technology development program to solve. In addition, enhancements to the NIF baseline, such as specialized focusing, higher bandwidth and beam smoothing for direct drive, and possibly a short-pulsed laser capability, will require support by laser technology development programs at HEDP institutions.

Pulsed-power technology is a leading candidate as the next-generation driver for a high-yield facility. Z, at SNL, relies on 15-year-old technology, and the facility has evolved from a particle accelerator to a z-pinch, x-ray source. In addition, experiments have evolved, becoming more sophisticated and complex, which produces new demands for increased machine performance. Recently, SNL used the Z-machine to produce planar magnetic fields to isentropically compress material and to accelerate flyer plates for materials dynamics studies. SNL maintains a pulsed-power development program to meet these demands. Some areas of development are improved pulse triggering and switching, pulse shaping, more efficient transmission and energy delivery, and improved diagnostics and modeling capabilities.

The HEDP program also has a development program in high-average-power lasers, mandated by Congress. It supports technology development in KrF gas lasers at NRL and diode-pumped solid-state lasers at LLNL. NRL is currently building the Electra laser, to be complete in FY 2005. Electra will be a 5-Hz, 700-J laser, and has a long-term goal of demonstrating that the technology is scalable to MJ-class systems. LLNL is presently building the Mercury laser, which will provide 100 J of energy at a frequency of 10 Hz, using solid-state laser technology that is scalable to inertial fusion energy drivers.

3.4.9 MAINTAIN THE U.S. PREEMINENCE IN HED SCIENCE AND SUPPORT BROADER NATIONAL SCIENCE GOALS.

The U.S. has long been preeminent in HED science, largely through DP's ICF Program. HED science is one key to maintaining confidence in the U.S. nuclear deterrent. It does this by providing essential science tools and understanding for maintaining the present nuclear stockpile and by nurturing a community of world-class HED scientists, both within and outside the NNSA national laboratories. To best maintain confidence in nuclear deterrence, the U.S. must continue to maintain its leadership in this key nuclear weapons field. Executing the broad program of activity DP has set forth in the baseline HEDP Program for the next decade will maintain this U.S. preeminence.

Although not in the main mission of the HEDP Program, some of its activities support broader national scientific goals. These include, but are not limited to, the demonstration of ignition and high gain in the laboratory for inertial fusion energy, pursuit of fundamental scientific HEDP research, development of scientific and engineering excellence in the U.S., maintaining favorable and vital research programs with U.S. Allies, and development of technologies for a potential high-yield facility. In each of these areas, members of NNSA/DP, along with other federal agencies and external organizations, strive to optimize activities that best serve these broader national goals. In the cases of ignition demonstration and high-yield driver research, NNSA/DP partners with OFES. In cases of pursing fundamental research and development of scientific and engineering excellence, DP partners with other organizations, including the DOE's Office of Basic Energy Sciences (OBES).

3.4.10 MAINTAIN AWARENESS OF INTERNATIONAL ACTIVITIES AND NURTURE APPROPRIATE INTERNATIONAL COLLABORATIONS IN HEDP SCIENCE AND TECHNOLOGY

The HEDP program participates in international activities that allows fruitful scientific discourse while minimizing possible contribution to proliferation of nuclear weapon technology. The activities include publication of technical papers, participation in international conferences, contracting with international organizations, and formal international cooperation. Formal international agreements are bilateral and provide direct benefit to ongoing HEDP science and technology research and development (R&D). In particular, the U.S. HEDP Program has had long and productive relationships with the United Kingdom and France. These international activities maintain U.S. program awareness of related international activities and enhance the cost efficiency and effectiveness of the HEDP program by nurturing international HEDP involvement. The international involvement also assists the OFES in their efforts to develop inertial confinement fusion as a future energy source.

3.5 International Collaborations

The ICF Program cooperates with laboratories abroad, when appropriate. A formal DOE/CEA agreement has resulted in a productive collaboration among LLNL, LANL, UR/LLE, and the CEA laboratories in the areas of NIF laser technology development and target physics. ICF scientists actively participate in weapons physics experiments and other activities sponsored under existing treaty agreements with the Ministry of Defence (MOD), in the United Kingdom (UK). Individual ICF Program scientists have collaborated with colleagues around the world, including those in the UK, France, Japan, and Russia. The ICF Program has benefited from international cooperation, by allowing results of international research to be incorporated in a timely and efficient manner. Statements by France and the UK, regarding the importance of high-energy-density physics in their stewardship activities, are contained in Appendices F and G, respectively.

The "Agreement Between the U.S. Department of Energy (DOE) and the Commissariat à l'Énergie Atomique (CEA) of France for Cooperation in Research, Development, and Applications of High Energy Laser and High Energy Laser-Matter Interactions Physics" was signed in 1987. It currently includes collaboration in the development of advanced laser systems, components, materials, and materials manufacturing technologies for megajoule-class, solid-state laser facilities. This supports both the NIF Project and the Laser MegaJoule (LMJ) project in France. As part of the cooperation, France has contributed $100 million to NIF/LMJ technology development.

Under the auspices of the "U.S.-UK 1958 Agreement on the Uses of Atomic Energy for Mutual Defence Purposes (as amended)," the ICF Program cooperates in high-energy laser science. This has resulted in a long, successful relationship in the area of nuclear stewardship using high-power lasers. Currently an expanded cooperation is being planned that would include a shot-rate enhancement program to increase the number of NIF shots per year, providing capacity for shots for UK experiments.

Finally, the ICF Program cooperates under a bilateral agreement with France in the development of fast (i.e., nanoseconds) pulsed-power technology. The agreement, "Technical Arrangement Between the U.S. DOE and the Minister of Defense of the French Republic Concerning Cooperation in the Application of Emerging Technologies," was signed on May 9, 2000. The technical goals include the development of concepts and new technologies for pulsed accelerators. In particular, this arrangement should propel development of large-pulse power x-ray sources, while optimizing the radiation fields produced by z-pinches in vacuum enclosures. The principal benefit is rapid development of pulsed-power accelerator concepts and technologies for stockpile stewardship, at a lower cost than could be accomplished by the U.S. alone. SNL and the Centre d'Études de Gramat (CEG) of the Délégation Général pour l'Armement (DGA) for France are the principal participants in the cooperative activities under the "Technical Arrangement."

3.6 Summary of Previous Reviews

The ICF program, a major portion of the HEDP Program, has been reviewed extensively, including its plans for NIF. A compendium of the major reviews of the ICF program and NIF are listed in Appendix 8. Relating to NIF, most of the early reviews focused on policy, mission need, and technical readiness for ICF and weapons physics. After the beginning of the NIF Project additional reviews focused on the cost, scope, and schedule of the project.

The NAS review in 1989, directed by Congress, evaluated a number of issues relating to the ICF program. The final report issued in 1990 had a number of specific recommendations concerning the direction of the ICF program.[11] The report reaffirmed the role of ICF as a defense program and recommended that "The expeditious demonstration of ignition and gain should be the highest priority of the ICF program." To implement this recommendation, the committee further recommended that "funds be provided for Precision Nova and the associated experimental campaign."

This established the "Nova Technical Contract," defining the physics program required before proceeding to the next

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[11] "Second Review of the Department of Energy's Inertial Confinement Fusion Program, Final Report", National Academy of Science, September, 1990.

facility. They also recommended that "A beamlet of the proposed laser architecture (of the next facility) should be constructed and demonstrated," and that "The only possible technology for a near-term ignition demonstration is the mature solid state laser." They also recommended establishing an Inertial Confinement Fusion Advisory Committee (ICFAC) to provide guidance to DOE.

ICFAC was established in 1992 under the Federal Advisory Committee Act (P.L. 92-463), in response to the NAS recommendation. Twelve meetings were held from 1992 to 1995. The conclusions of the committee for the beamlet was that "Beamlet, a single beam prototype to address critical laser design issues for NIF, has met the beam specifications."[12] They continued to recommend to follow through on evaluating remaining issues. For target physics they observed that the work on the original Nova Technical Contract "is essentially complete."[13] They also stated that "Most of the committee members believe that the probability of ignition has increased above 50 percent, and some believe that it is well above this level."[14]

This led to the following recommendation: "The committee recommends as far as ignition is concerned there is sufficient evidence that the program is ready to proceed to the next step in the NIF project."[15]

An NAS review was undertaken, beginning in 1996, to determine the scientific and technology readiness of NIF and to evaluate the relevance of the ICF program to SSP. The committee convened six times during approximately eighteen months and published their report in March, 1997.[16] In it the committee's findings and recommendations were that "The NIF would make important contributions toward the stated long-term goals of the SBSS [Science-Based Stockpile Stewardship] Program" and "The science and technology have progressed sufficiently to allow the NIF Project to proceed as planned."

The JASON committee also evaluated NIF and ICF's role in SSP during two reviews. The first review in November, 1994, chaired by Dr. Sidney Drell, evaluated the SSP in general. They identified the strong role that NIF and ICF research play in SSP. In their report,[17] they stated that The NIF is without question the most scientifically valuable of the programs proposed for the SBSS, particularly in regard to ICF and a 'proof-of-principle' for ignition, but also more generally for fundamental science."

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[12] Letter from Dr. V. Narayanamurti, Chair of ICFAC, to Dr. V. Reis, DOE, Oct. 2, 1995.
[13] Ibid.
[14] Letter from Dr. V. Narayanamurti, Chair of ICFAC, to Dr. V. Reis, DOE, Oct. Feb. 21, 1996.
[15] Ibid.
[16] "Review of the Department of Energy's Inertial Confinement Fusion Program, The National Ignition Facility", National Academy of Sciences, March, 20, 1997.
[17] "Science Based Stockpile Stewardship", JASON – The Mitre Corporation, JSR 94-345, Nov. 1994.

In support of this claim they enumerated many of the reasons discussed in this report, such as access to extremely high energies and densities, maintaining the "core intellectual competency," and attaining ignition will demonstrate an integrated mastery of physics relevant to nuclear weapons. The 1996 JASON study reaffirmed the strong role NIF would play in SSP. In their report,[18] they stated that that "the ICF program is an important element in the SBSS program now, and we reaffirm our previously stated support for proceeding to the next step of achieving ignition with the NIF."

The NIF Project has had many reviews both internal and external to DOE. DOE has reevaluated NIF prior to proceeding with each major steps of the NIF Project such as the Conceptual Design, Project Start, and Construction Start. Also, two independent cost estimate reviews were performed after the conceptual design and completion of Title I design. An additional independent cost assessment was done in 1998-99, as mandated by Congress. The Project has held major design reviews at each step in the design process. Most recently the Project underwent a major independent review of its re-baseline prior to being approved by DOE.

The NIF and its relationship with nonproliferation have been thoroughly studied. In November 1997, a JASON study found that "NIF technology is not a nuclear weapon, cannot be adapted to become a nuclear weapon, and demands a technological sophistication far more advanced and difficult than required for nuclear weapons." At the direction of then Secretary of Energy, Hazel O'Leary, a NIF Nonproliferation Study was carried out in 1994-1995, by DOE's then Office of Defense Nuclear Nonproliferation. The study concluded

- "The technical proliferation concerns at NIF are manageable and therefore can be made acceptable," and

- "NIF can contribute positively to U.S. arms control/nonproliferation goals."

Furthermore, both the JASON and the NIF Nonproliferation Study recommended enhanced international cooperation, based on NIF, to demonstrate compliance with the Non-Proliferation Treaty (NPT) and the Comprehensive Test Ban Treaty (CTBT). A DP-sponsored follow-up study, conducted by Science Applications International Corporation (SAIC) in 1997, recommended specific implementation measures, such as transparency and restricting international participation at NIF to individuals from states participating in the NPT and CTBT.

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[18] "Inertial Confinement Fusion (ICF) Review", JASON – The Mitre Corporation, JSR 96-300, March 1996.

The Foster Panel says in their FY 2000 report to Congress:[19]

> "The National Ignition Facility (NIF) is the next logical step in a basic research program in high-energy density physics that has been conducted until recently at the Nova laser facility.
>
> "We have not examined the technical and programmatic problems associated with the development and construction of this facility, which have received national attention. We have, however, received briefings and documentation concerning the relevance and importance of NIF to stockpile stewardship. We are convinced that NIF could offer critical insights into stewardship problems that are inaccessible otherwise. In the FY01 Defense Authorization Act, Congress required review of the NIF program and problems. We offer a few observations that we believe are important and relevant:
>
> - "It is very important that the NIF produce ignition in order to address a new range of stockpile issues, but ignition is not assured even for full-power NIF. The subset of issues that could be addressed short of ignition is also important, but a half-power NIF without ignition is not worth the investment for stockpile stewardship. We believe that ignition should be the prime stated goal.
> - "Unclassified research is also important, but must not be to the detriment of stockpile stewardship. The capability and schedule must be driven by stewardship needs. Outside users are beneficial to the laboratories scientific environment, to the continued excellence of the laboratories' basic research program, and are potential contributors to stewardship. The continued excellence of the nuclear laboratories' basic research programs and the capability to sustain confidence in the stockpile are certainly linked. However, stockpile stewardship needs should have first priority."

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[19] *FY 2000 Report to Congress of the Panel to Assess the Reliability, Safety, and Security of the United States Nuclear Stockpile*, February 1, 2001. The Panel included Harold M. Agnew, John S. Foster, Jr., (chairman), Sydell P. Gold, Stephen J. Guidice, and James R. Schlesinger.

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CHAPTER 4

Accomplishments of the HEDP Program

4

Accomplishments of the HEDP Program

The SSP is in place and is successfully sustaining the U.S. nuclear weapons stockpile. Significant stockpile actions have been accomplished since its inception, including the development and production of the B61-11, an earth-penetrating strategic nuclear bomb to replace the aging B53. More actions are currently underway, such as the W87 LEP. Several actions are in planning and development stages, including manufacture and certification of W88 pits and LEPs for the W76-1, the W80-2/3, and the B61-7/11 nuclear weapons. In all of these stockpile actions, new tools developed by the SSP have been used to identify issues, analyze potential impacts, develop solutions, implement changes, and, in the case, of completed stockpile actions, support continued certification of the weapons.

4.1 Weapons Physics and Code Validation

New computer codes, incorporating updated physics data and capable of more detailed and complex calculations required by these programs, were validated, in part, through experiments conducted on HEDP facilities. Some weapon issues include the potential effects of changes due to aging, or effects due to slight differences in manufacturing processes that are used or proposed for weapon refurbishments. In addition to experimental validation of the modeling capability, HEDP experiments provide better fundamental physics data, reducing uncertainties in the simulations. Examples of fundamental physics data include follow.

- Hydrogen EOS– EOS experiments on hydrogen isotopes revealed important behavior at Mbar pressures, highlighting the difficulties with theories of matter undergoing strong shocks. For example, gas gun experiments have succeeded in “metallizing” fluid hydrogen under shock-loading conditions above 1.4 Mbar. The existence of a metallic phase of hydrogen confirms a fundamental prediction made 50 years ago.

- Laser-Driven Nuclear Physics – As part of the studies related to NIF and laser-driven radiography, observations of nuclear physics phenomena produced by the interaction of an extremely powerful laser with matter have been performed. In particular, measurements of the production of 100 MeV electrons, the fission of nuclei, and the production of anti-matter have been performed.

- Gold Opacity Measurements – Recent opacity experiments on the Nova and Omega lasers have extended Rosseland mean opacity measurements into new areas. Opacity measurements of high temperature gold plasmas have resolved large differences between opacity models that affect the design and interpretation of a large class of stockpile stewardship experiments on lasers and pulsed power devices. The experiments have also proven the techniques needed for the high temperature opacity experiments proposed for the NIF.

- Multi-laboratory radiation-flow experiments have been performed on ICF facilities, Nova, Omega and Z, confirming that aboveground experiments (AGEX) experiments coupled with detailed modeling can meet weapons physics goals.

- EOS experiments on deuterium at the Nova laser won the Excellence in Plasma Physics Award of the American Physical Society. These results impact analysis of weapon performance and provide improvement of anticipated ignition experiments at NIF.

- A quantitative testbed for radiation flow has been developed, characterized, and used for validation of codes.

- The effects of strength of materials on Rayleigh-Taylor instabilities at high pressure has been demonstrated and measured.

4.2 Ignition

The U.S. has maintained a vigorous HEDP Program, striving to achieve ignition in the laboratory, since the early 1970s. Theoretical estimates of the requirements for ignition spurred the construction of high-powered lasers and pulsed-power facilities at LLNL, LANL, SNL, and the University of Rochester. Although these initial, large facilities met or surpassed their designed performance, they proved inadequate to achieve the programmatic objective of achieving ignition. Their research, however, helped develop an understanding for the next generation of facilities at LLNL, SNL, the University of Rochester, and NRL. These newer facilities have helped to develop an underlying physics understanding necessary for defining the technical requirements for ignition.

The baseline approach for achieving ignition at NIF is to use indirect x-ray drive. Significant accomplishments have contributed to the physics understanding of indirect-drive ignition, resulting in confidence in achieving ignition at NIF. These accomplishments include

- Halite and Centurion experiments, using nuclear explosives, that put to rest fundamental questions about the basic feasibility of achieving high gain,

- Development of a wide range of ignition target designs, spanning laser and target parameter space, by both LLNL and LANL, that are predicted to ignite with less than two megajoules of laser energy,

- A demonstration of laser hohlraum energy coupling, with low preheat, at a level required for NIF ignition designs, through experiments on Nova,

- A demonstration of detailed predictive understanding of the time-dependent radiation drive from absorbed laser energy in hohlraums, through experiments on Nova,

- Demonstration of predictive understanding of the hydrodynamic physics of indirectly driven targets, through experiments on Nova,

- Demonstration of the radiation-drive symmetry control required for NIF ignition targets, through experiments on Omega, using a multi-ring, NIF-like illumination geometry (see Figure 4-1),

- Demonstration of indirectly driven, ignition-like, high-convergence spherical implosion on Nova and Omega, whose performance are well predicted by detailed two- and three-dimensional computer simulations,

- Development of advanced target-coupling concepts, significantly increasing the margin for achieving ignition at NIF, with possible application to high yield (~100 MJ) designs,

- Development of concepts for symmetric x-ray drive implosions using pulsed-power drivers,

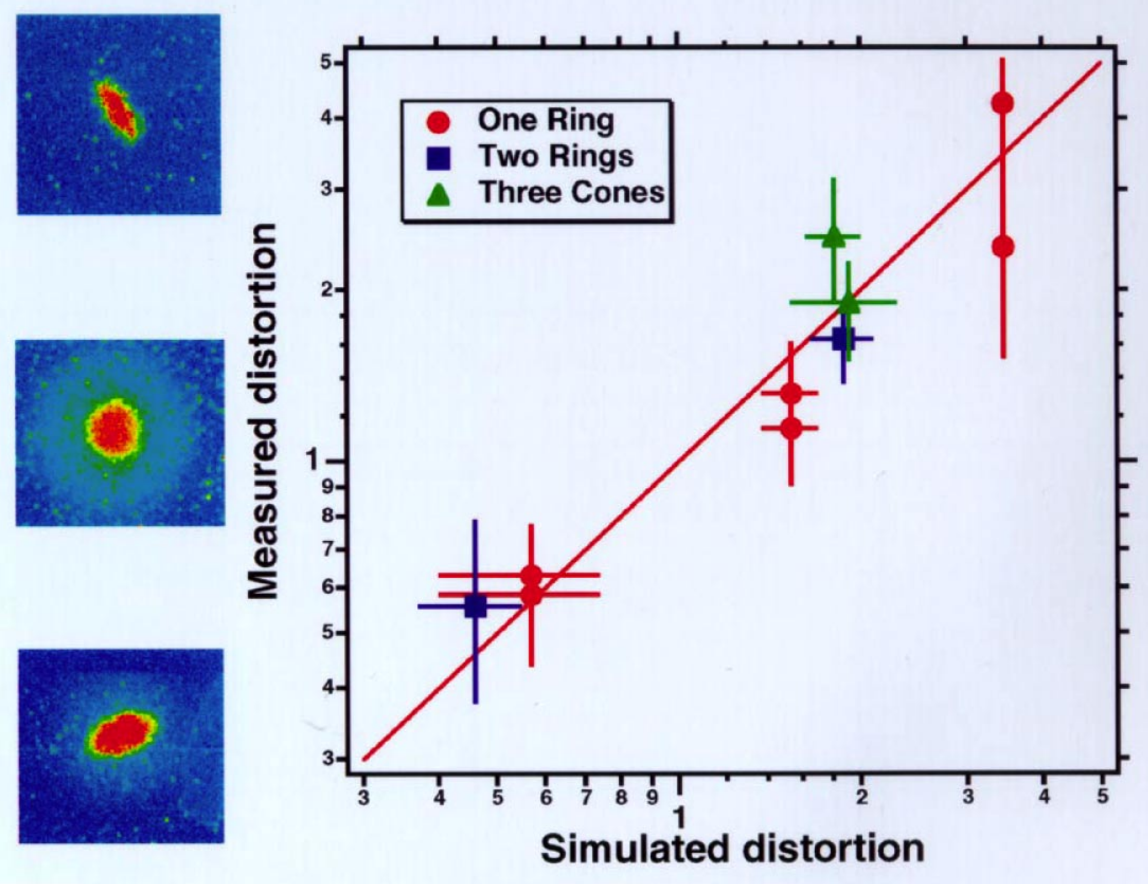
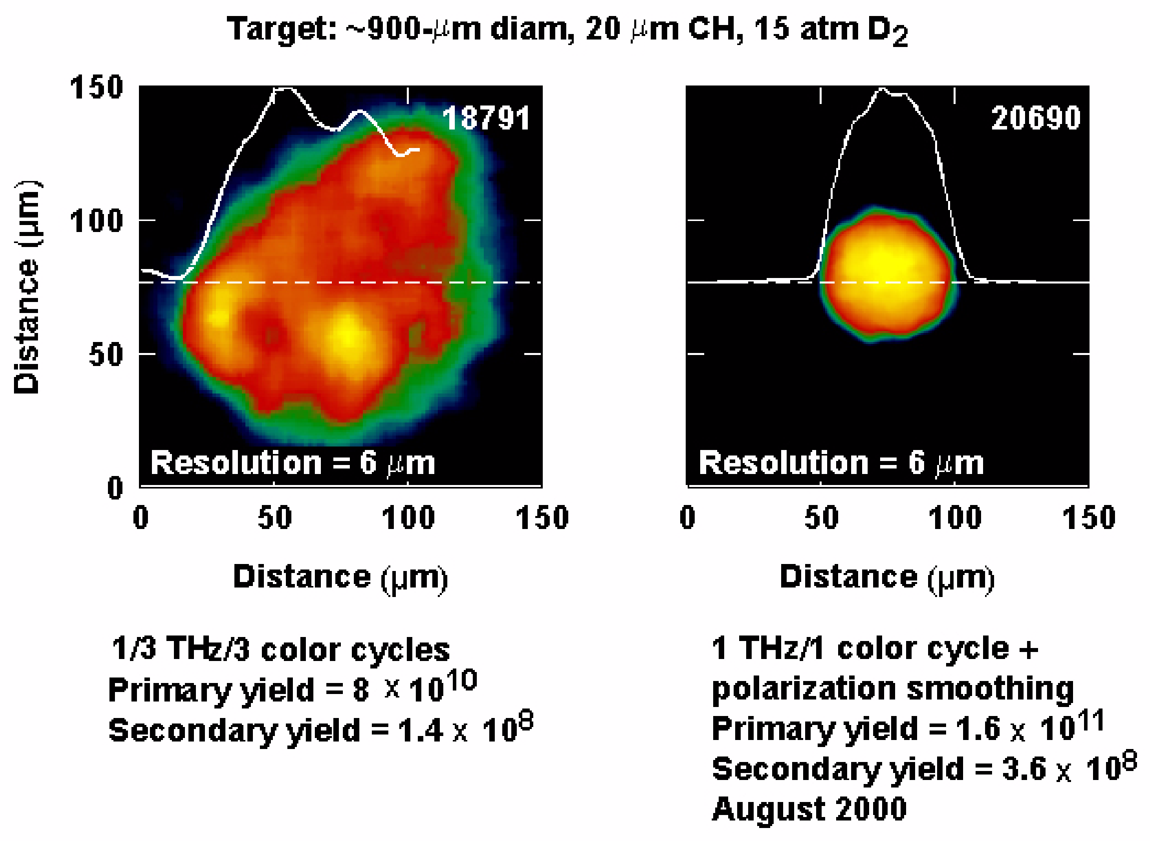


Figure 4-1. Experiments have shown that implosion symmetry can be predictively controlled to produce symmetric implosions. Data are from indirect-drive experiments performed on the Omega laser. Simulations performed by both LANL and LLNL using the LASNEX simulation software.

Direct x-ray drive is a complementary approach for achieving ignition. Although the physics basis for direct-drive ignition is presently not as well developed as for indirect drive, significant progress has been made recently using the Omega and Nike lasers. Experiments are continuing toward development of the physics understanding necessary for achieving direct-drive ignition at NIF. Significant accomplishments in direct drive are

- beam smoothing techniques, developed to produce smooth symmetric illumination,
- demonstration of efficient hydrodynamic coupling of short wavelength lasers,
- establishment of irradiation-symmetry beam-smoothing criteria, based on cryogenic direct-drive implosions at Omega,
- achievement of record neutron yields, using the upgraded Omega laser,
- quantification of beam imprint effects, using the Omega and Nike lasers, and
- demonstration of improved implosion performance at Omega, using the techniques of smoothing by spectral dispersion (SSD) and polarization smoothing.


Target: ~900-μm diam, 20 μm CH, 15 atm D_2

1/3 THz/3 color cycles
Primary yield = 8 x 10^{10}
Secondary yield = 1.4 x 10^{8}

1 THz/1 color cycle +
polarization smoothing
Primary yield = 1.6 x 10^{11}
Secondary yield = 3.6 x 10^{8}
August 2000

Figure 4-2. Smoothing of Omega laser beams leads to a more tightly compressed fuel region in the target capsule image and a factor of two increase in fusion reactions.

4.3 High Yield

The short-term goal of high-yield research in pulsed power is to develop a credible scenario for high yield with ~1 million joules absorbed in a fusion capsule. The assessment will be based on a validation of the z-pinch driver and indirect-drive target requirements, obtained by scaling key parameters from Z experiments using analytic modeling and sophisticated code simulations. In the high-yield z-pinch concept, electric currents produce an ionized gas, or plasma, by vaporizing a spool-of-thread-sized array of wires or an annular foil or puff of gas. The powerful magnetic fields created by these currents surround the plasma and "pinch" or implode it onto a vertical axis – hence the name "z pinch" – to densities and temperatures that will be sufficient to generate an intense source of x rays that implodes a fusion capsule to high yield. The long-term goal of the effort is to design, construct, and operate a high-yield z-pinch facility for the HEDP Program. Even though most weapon science applications do not require ICF capsules, emphasizing the radiation needed to implode a high-yield capsule in developing the scenario will ensure that such a facility meets most of the technical and experimental requirements of the HEDP Program.

The accomplishments in the high-yield z-pinch assessment arena have included:

- the demonstration, over a 15-year-period on four generations of pulsed-power facilities (SuperMite, Proto II, Saturn, and Z), that the x-ray energy produced in a z-pinch implosion scales as the square of the current;

- the discovery that an annular array of many (200 to 400) wires is an attractive pulsed power configuration that minimizes nonuniformities, improves the quality of the pinched plasma and its reproducibility, and, on Z, generates a powerful (~200 TW) source;

- the confinement, beginning in 1997 on Z, of the intense x-ray energy produced by such a wire array within a 5-cubic-centimeter metal case, thereby enhancing the spatial uniformity of the x-ray radiation and heating the case (often referred to as a hohlraum, or "hollow room") to radiation temperatures in excess of 150 eV (1.8 million degrees Celsius);

- the development and initial evaluation of two complementary high-yield fusion target designs for imploding z pinches;

- the demonstration on Z that the z-pinch technology that drives both of these target concepts is efficient (>15 percent conversion of electrical energy to x rays) and, at the 20-MA level, yields x-ray energies of up to 2 MJ;

- the refinement of a high-yield concept using two z pinches (called the z-pinch-driven hohlraum concept) by comparing the measured symmetry of irradiation of a "surrogate" capsule on Z with sophisticated code calculations; the concept demands precise timing of two nearly identical imploding pinches to avoid damaging radiation asymmetries and a driver energy of 16 MJ (60 MA to each pinch) to produce a yield of 380 MJ from the fusion capsule;

- the simulation, with radiation-hydrodynamics and radiation-magnetohydrodynamics codes, of the interaction of an imploding z pinch with a foam-filled cylinder and the design of a high-yield concept that uses a dynamic (imploding) hohlraum and a single z pinch to achieve an efficiency of 20 percent in absorbing energy into a capsule that is centered within the foam; the concept demands good control of radiation symmetry and instability growth and a single, 54-MA z pinch that generates 12 MJ in x-rays and produces a fusion yield in excess of 500 million joules;

- the first attempts to fabricate, field, and diagnose large capsules filled with D_2 or H_2 that are embedded in dynamic hohlraums and driven by x-rays from a z pinch.

Additionally, designers have developed a family of scaled targets, with yields from 19 MJ for use at NIF (144 kJ absorbed) up to a 3-GJ target for high-yield testing and fusion energy (4.5 MJ absorbed).[20] As absorbed energy is increased, work on high-yield designs and increased hohlraum coupling efficiency has opened new areas of inquiry, such as 1) decreasing marginal radiation temperature (low-temperature drive), 2) increasing absorption efficiency by decreasing case-to-capsule ratio, and 3) increasing available drive temperature by decreasing wall losses through use of high-opacity "cocktail" mixtures. In addition to increased hohlraum coupling efficiency, there are operational strategies that may allow more energy to be extracted from a 192-beam NIF than had been previously assumed. For example, using a technique known as "ultrafast pickets,"[21] it is conceptualized that a 192-beam NIF might be able to drive target capsules corresponding to yields of ~50 to 150 MJ and energy gains of 25× to more than 40×.

All of the high-yield capsules described in this section utilize cryogenic DT fuel and hot spot ignition. Of potential SSP interest is an SNL-designed "warm-ignition" target, based on the single-pinch concept, yielding 4 MJ fusion output from a gas-filled capsule driven by a 54 MA z-pinch implosion. This is a non-cryogenic variant of the dynamic-hohlraum, high yield point design that absorbs 2.3 MJ into the capsule. Finally, in an attempt to understand and enhance the yield and gain from ICF targets, designers are also studying the potential advantages of fast ignition as an alternative to hot spot ignition of DT fuel.

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[20] Hermann, M.C. Tabak, M., Lindl, J.D. 1999, submitted to Nuclear Fusion.
[21] J. Rothenberg, "Ultra-fast pickets", private communication (LLNL,1999).

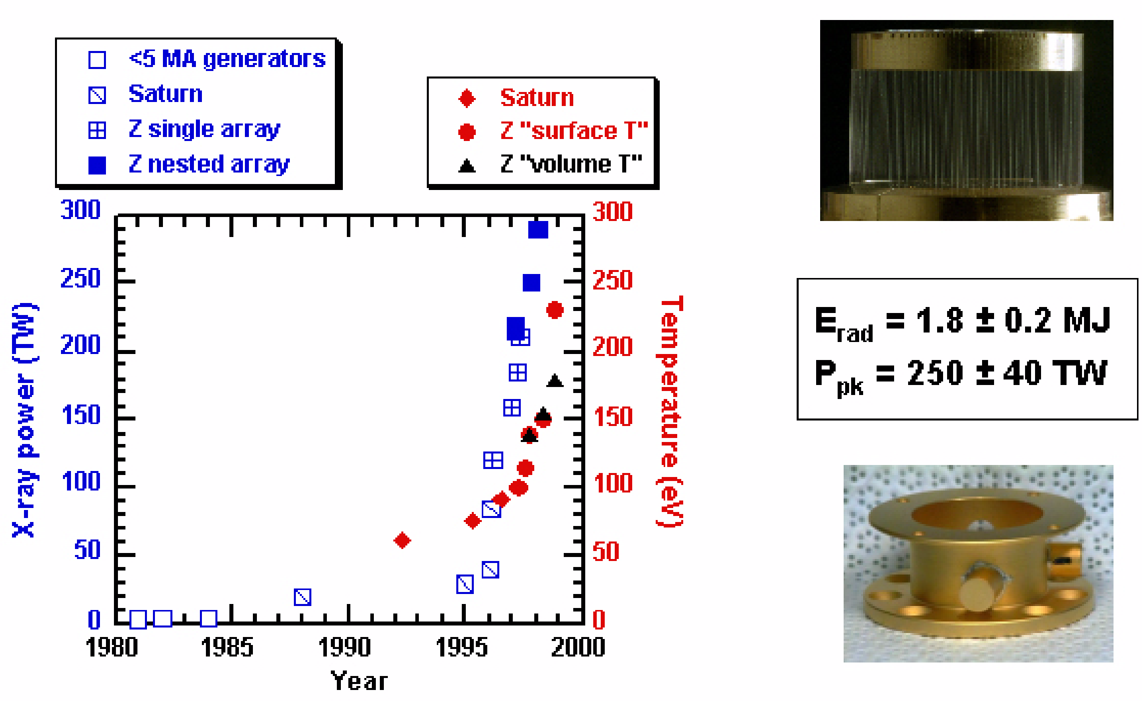

Figure 4-3. Record x-ray powers have been demonstrated on the Z accelerator.

4.4 Weapons Effects

With the cessation of underground testing, high fidelity sources of cold and warm x-rays for weapons effects testing were lost. Recent advances, during the 1990s, in z-pinch physics on pulsed-power drivers have had a significant impact on weapon effects testing. The major HEDP z-pinch experimental tools for generating >1 keV x-rays for weapon effects are the Z and Saturn pulsed-power facilities. The yield of titanium K-shell x-rays at the Z facility (130 kJ at 4.8 keV) is more than an order of magnitude greater than any other laboratory source at this energy and provides new capability to stimulate samples to the region of interest for developing models for cable SGEMP. Similarly, the yield of molybdenum L-shell x-rays at the Z facility (135 kJ at 2-3 keV) provides sufficient fluence on coupons to vaporize heat-shield materials, providing data for the development of models of impulse loading on reentry bodies.

Joint work between LLNL, DOE, and the Defense Threat Reduction Agency (DTRA) has resulted in a number of enhancements and modifications to the NIF facility. Large target-chamber ports and flexibility in beam steering and focusing will provide distributed x-ray sources for effect testing. In supporting development work, sources radiating in the range of 4-5 keV have been demonstrated experimentally using Nova, Omega, and Helen (a .9-kJ, 1-TW pulsed laser at the UK Atomic Weapons Establishment) with x-ray conversion efficiencies of approximately ten percent.

4.5 Basic Science

The HEDP Program supports basic research at the DP national laboratories, universities, and other research institutions for developing an underlying understanding of the physics of the operation of nuclear weapons and for areas of broader national interests. Support for this effort comes from the HEDP Grants Program, the National Laser User Facility, and direct programmatic funding from the NNSA national laboratories. The basic science experiments and grants cover a wide array of physics areas including radiation hydrodynamics, laser-plasma interactions, atomic physics of highly ionized matter, dense matter physics, and high field laser-matter physics. Until its closure in 1999, the Nova facility at LLNL had a successful Scientific Use of Nova (SUN) program that provided experimental time on the Nova laser for peer-reviewed, basic-science experiments. In addition, the HEDP Program is on the forefront of technology in driver and diagnostic development. Examples of the science and technology accomplishments outside nuclear weapons development are described below. This list is not intended to be exhaustive, but it highlights the breadth and impact of the HEDP Program.

Some high-energy-density conditions produced during the operation of nuclear weapons are similar to those observed in astrophysics. Consequently, these two communities share basic research interests in common areas, such as physical properties of matter-like opacities, EOS, nuclear reaction data, radiation hydrodynamics, and large computer simulation algorithms. Until recently, astrophysics modeling and predictions were tested almost entirely using celestial observations. Recently, scaled experiments have been shown capable of testing astrophysics modeling and predictions, by augmenting observations with experiments at HEDP facilities. For example, modeling of the 1987 supernova explosion predicted bright emissions, due to shock propagation, that subsequently were observed astrophysically. Scaled experiments using the Nova laser[22] were able to test these predictions before the predicted astrophysical events were observed. This capability has resulted in a new sub-field of research being formed in the American Physical Society.

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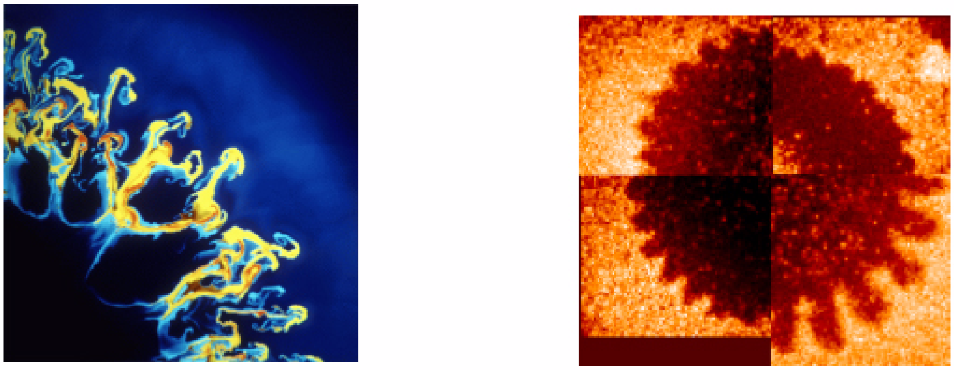
[22] B. A. Remington, R. P. Drake, H. Takabe, and D. Arnett, "A review of astrophysics experiments on intense lasers," Phys. Plasmas 7 1641-52 (2000).



(a). Simulation of a supernova

(b) Data from a divergent geometry experiment on Nova

(c). Simulation of multilayer in a Supernova

(d). Data of scaled multilayer experiment on Omega

Figure 4-4. Data from scaled laboratory astrophysics experiments.

The EOS of a material defines the functional relationship of the thermodynamic properties relating pressure, density, and temperature of the system in equilibrium. EOS of materials directly impact understanding of astrophysical and planetary systems and ignition predictions for ICF, as well as conditions in nuclear weapons. Recent shock wave experiments at HEDP facilities extended the EOS measurements of deuterium to higher pressures and densities than previously obtainable by gas guns or diamond anvil cells. Although still being vetted in the scientific community, these results show a significant difference in the compressibility of deuterium than predicted by standard models. These new results directly impact the understanding of planetary cores such as Jupiter and the interior of the sun.

The interaction of high-powered lasers with matter produces non-linear interactions, such as stimulated Raman scattering (SRS), stimulated Brillioun scattering (SBS), and filamentation. In pulsed-power machines, the high fields and currents present interesting problems in magnetohydrodynamics. Studies in these areas have significantly advanced understanding in basic plasma physics. One example of cutting-edge research is in high-intensity, short-pulsed laser-matter interactions. Lasers that can produce intensities greater than 10^{19} W-cm^{-2} with pulse lengths of ≤ 1 ps have been developed in HEDP studies of alternative ICF concepts. At these high intensities, laser-matter interactions are highly nonlinear and relativistic effects become important. Experiments using a petawatt beam at Nova and at other facilities provide MeV electron and proton production, as well as many other phenomena stimulating basic physics research in this area.

Advanced technology development of drivers and diagnostics has contributed significantly to other areas of science and technology. Diagnostic technology developed for HEDP is contributing directly to new capabilities in medical technology diagnostics and procedures, such as non-intrusive surgery and monitoring and dose delivery. The enhanced surveillance program of the SSP is incorporating technology originally developed for diagnostics. For example, laser machining and cutting, using short-pulsed laser technology, have been demonstrated to improve performance for defense and industrial applications. The present approach to extreme ultraviolet (EUV) lithography being performed by a consortium of the federal government and semiconductor companies[23] uses laser-produced sources and EUV optics for which HEDP research contributed significantly to their development.

4.6 Supporting Technologies

Significant technology advances are required to implement the HEDP Program. Advances have been made in areas of driver technology, target technology, and diagnostics. Not only are these important for executing the program, some have impacts in other areas of science and technology.

A technology development program on Nd-glass lasers was undertaken to demonstrate NIF technology and to meet its cost goals. Some of the accomplishments in this area include

- Demonstration of large-aperture multipass laser performance using large-aperture Pockels cells on the Beamlet laser, allowing efficient laser energy extraction,
- Demonstration on the Beamlet laser of beam performance at the 1ω frequency required for NIF,
- Demonstration of the gain and uniformity goals of NIF amplifier design,
- Growth of large-aperture, frequency-conversion crystals, using new rapid growth technology,
- Manufacture of NIF laser glass, using a newly developed continuous-pour process, and
- Development of beam smoothing techniques for both direct and indirect-drive experiments.

Advances have also been made in fabricating ignition targets. Accomplishments include

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[23] D. A. Tichenor, et al., "EUV Engineering Test Stand," in *Emerging Lithographic Technologies IV*,E. A. Dobisz, Ed., Proceedings of SPIE, Vol. 3997,48-69 (2000)

- Demonstration of the capability to make cryogenic DT layers with sufficient smoothness,
- Development of enhanced smoothing techniques for cryogenic layering,
- Demonstration of the use of cryogenic capsules at Omega,
- Fabrication of plastic capsules close to NIF specifications,
- Demonstration of beryllium-shell machining of NIF capsules, and
- Initial design of a cryogenic hohlraum.

Figure 4-5. Cryogenic layering experiments at LLNL have demonstrated cryogenic hydrogen ice layers that meet the NIF ignition requirements for temperature and smoothness. The figure shows a 1 mm diameter polymer capsule containing a100-µm thick layer of HD ice that has been layered and smoothed by illumination with infrared laser light. The outside of the thin "bright band" images the ice surface and shows an rms roughness of 0.7 µm (modes 3-100) at a temperature 1.5 K below the melting point, as specified for the NIF ignition targets.

Diagnostic and measurement technology has made important progress. Some of the accomplishments include

- Demonstration of techniques to measure drive symmetry in hohlraums,
- Development of fast time-resolved imaging technology,
- Demonstration of charged particle spectrometers for measuring fusion products, and
- Development of large-aperture charge-coupled device (CCD) technology for diagnostic recording.

Advances are being made in pulsed-power technology. These accomplishments include

- Demonstration of efficient x-ray production on the Z machine, using single and nested wire arrays,
- Use of magnetic fields to directly accelerate flyer plates and to produce isentropic compression for materials research, and
- Development of improved liner-transformer technology that, along with incremental improvements in insulator breakdown, switching, and reproducibility control, could poten-

tially improve the reproducibility factor of the load current in the Z machine by a factor of two (reduce variability from five percent to two percent).

4.7 Summary

As is evident from the previous discussion, the HEDP Program carries out a wide variety of activities. This is demonstrated in Figure 4-5, which shows the FY 2000 shot allocations for the Omega and Z machines.

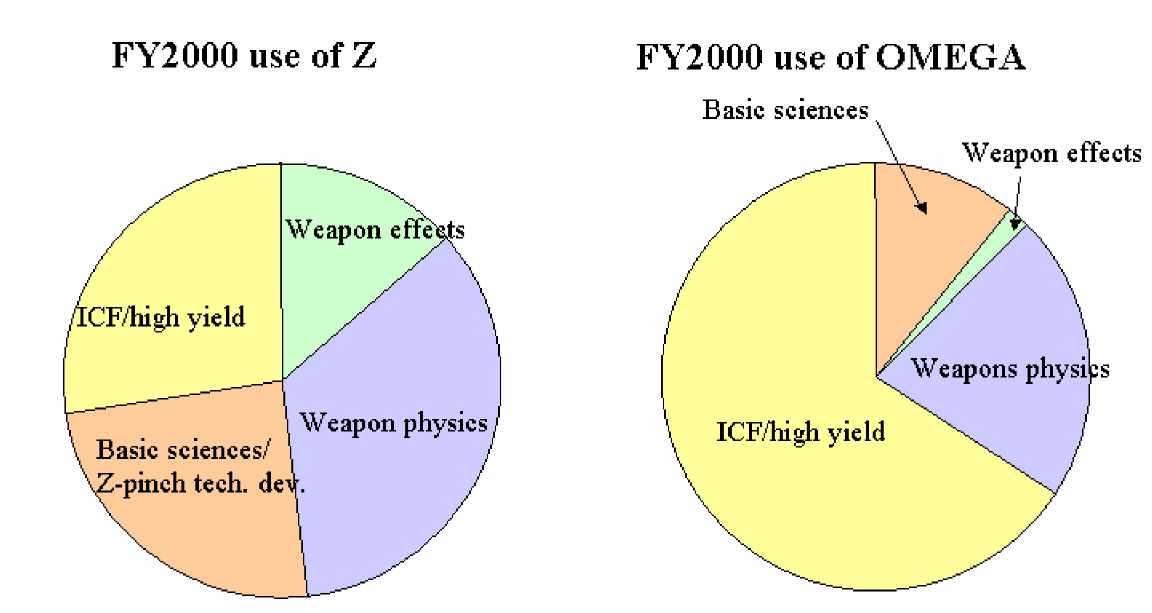


Figure 4-6. Facility usage in FY 2000 at Omega and Z.

CHAPTER 5

Alternative Strategies for Satisfying the HEDP Mission

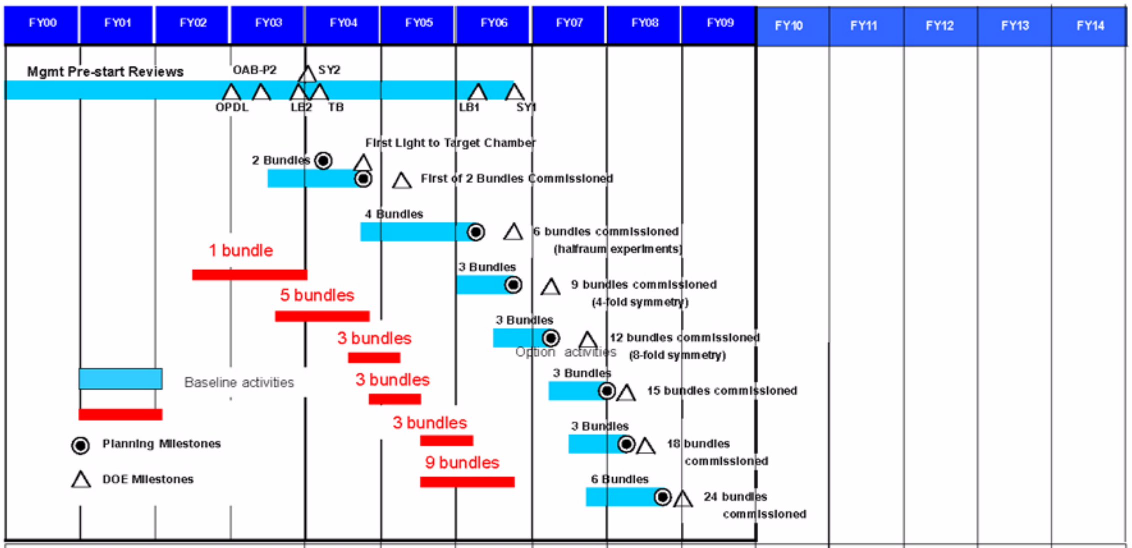
5

Alternative strategies for satisfying the HEDP mission

Alternatives to the current HEDP Program were solicited from the NNSA national laboratories. Their inputs are described below and included in Appendix I. Based on these submissions, NNSA defined a set of alternatives to be examined. These are summarized in Section 5.4.

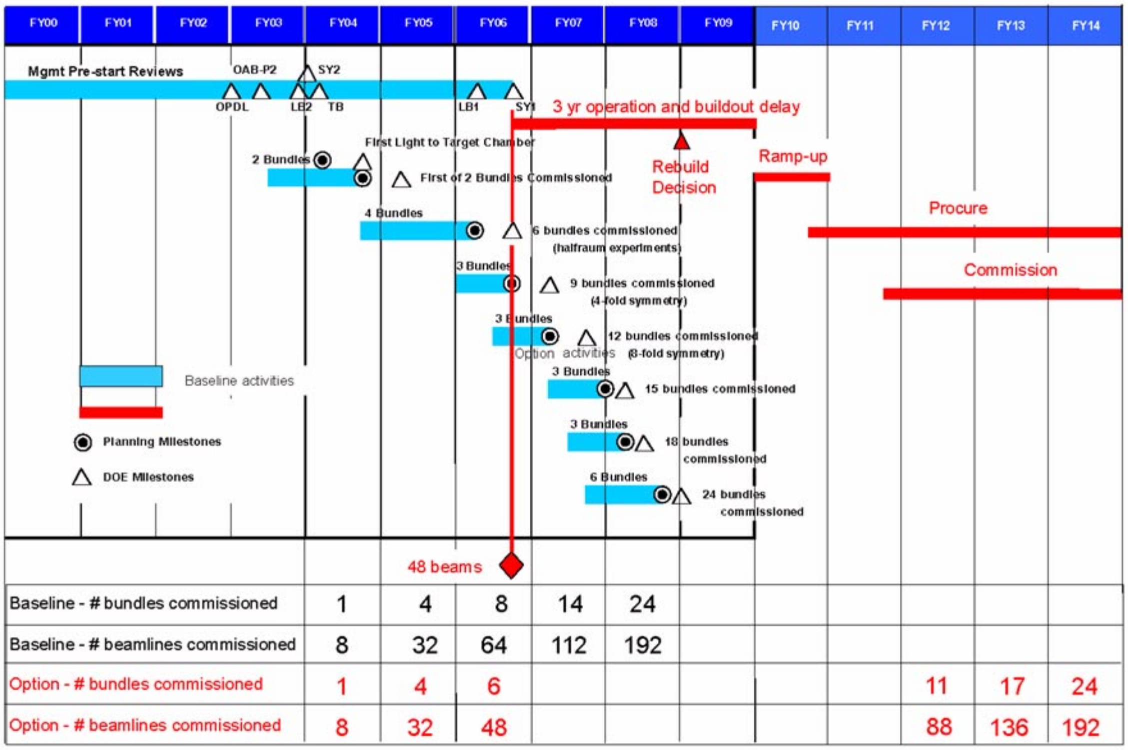
5.1 LLNL – Accelerated NIF

LLNL proposed that DP consider an acceleration of the NIF Project by two years, relative to its current baseline. The current baseline provides the first NIF cluster (48 beams), with operation using half-hohlraums (halfraums) in late FY 2006, and operation at the full 192 beams, by the end of FY 2008. The current schedule is perceived by LLNL to be longer than optimal for completing the project, and it delivers an operating facility several years later than is desired or optimum for HEDP experiments supporting the Campaigns and DSW. This proposed alternative accelerates the initiation of first-cluster experiments and completion of NIF by two years, to the ends of FY 2004 and FY 2006, respectively. This "optimum" schedule would require increased funding for FYs 2002 through 2005, relative to the current baseline, and would result in an overall lower total project cost (TPC), because of the earlier conclusion of the project (see Figure 5-1).



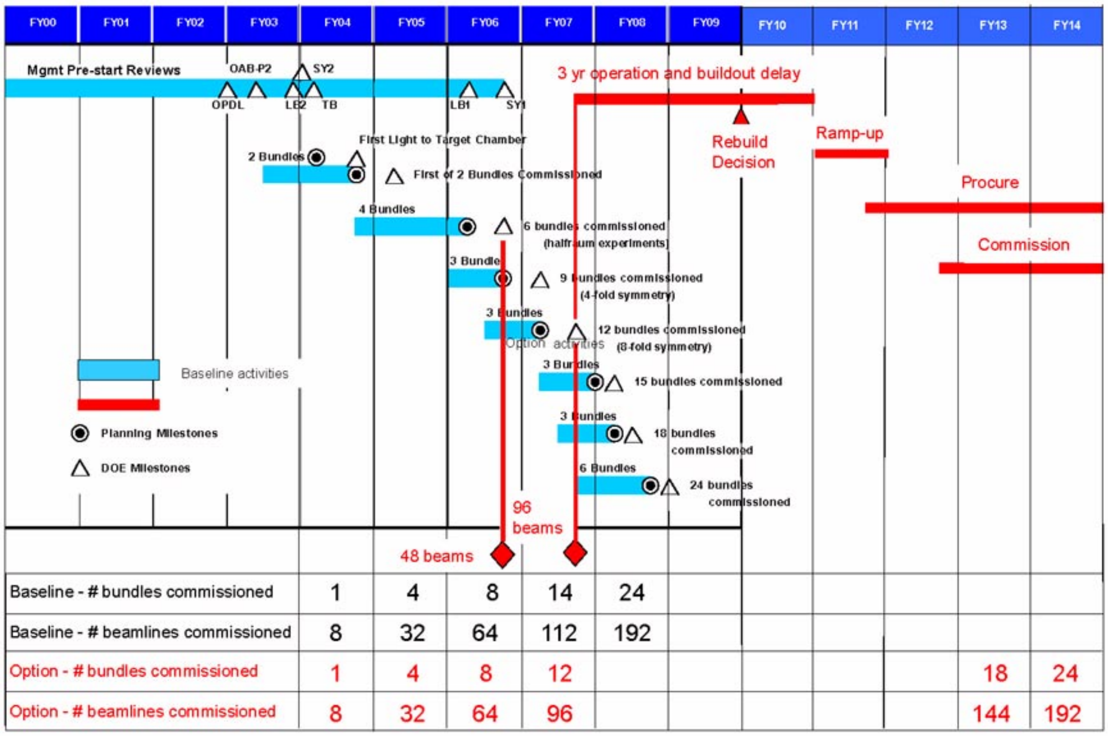
Baseline - # bundles commissioned	1	4	8	14	24						
Baseline - # beamlines commissioned	8	32	64	112	192						
Option - # bundles commissioned	6	12	24								
Option - # beamlines commissioned	48	96	192								

Figure 5-1. Optimized NIF option with project completion in FY 2006.



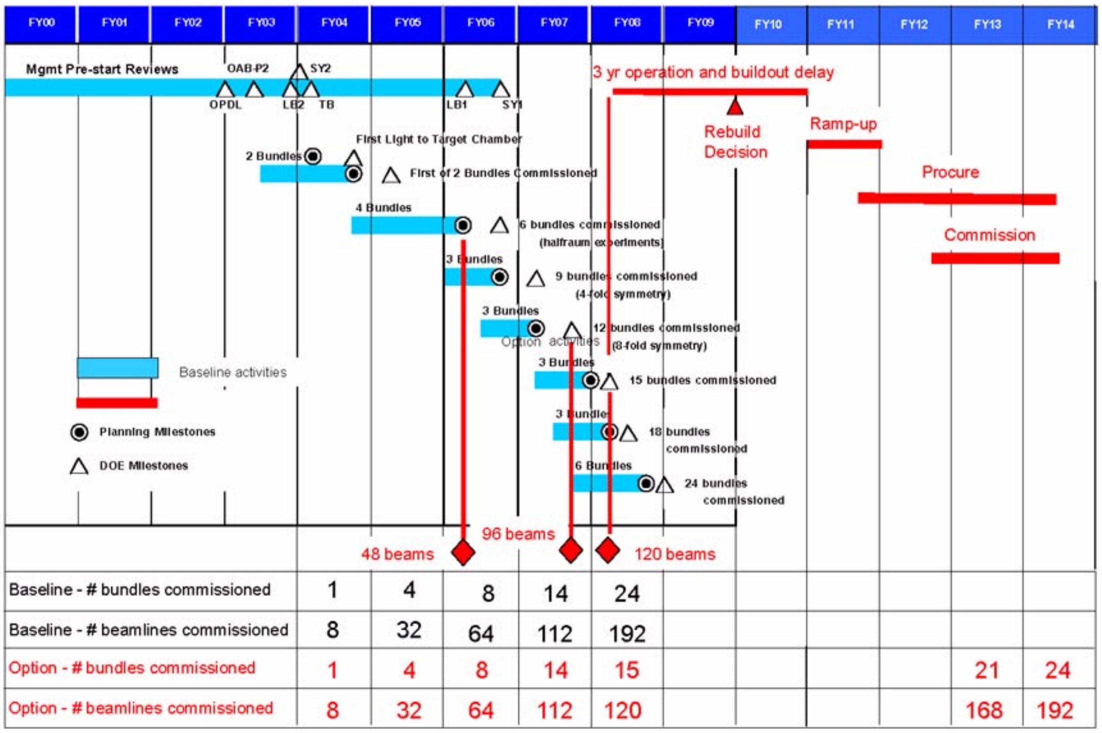
	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14
Baseline - # bundles commissioned	1	4	8	14	24						
Baseline - # beamlines commissioned	8	32	64	112	192						
Option - # bundles commissioned	1	4	6						11	17	24
Option - # beamlines commissioned	8	32	48						88	136	192

Figure 5-2. Availability of beams at NIF with a pause in construction at 48 beams.



	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14
Baseline - # bundles commissioned	1	4	8	14	24						
Baseline - # beamlines commissioned	8	32	64	112	192						
Option - # bundles commissioned	1	4	8	12						18	24
Option - # beamlines commissioned	8	32	64	96						144	192

Figure 5-3. Availability of beams at NIF with a pause in construction at 96 beams.



	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14
Baseline - # bundles commissioned	1	4	8	14	24						
Baseline - # beamlines commissioned	8	32	64	112	192						
Option - # bundles commissioned	1	4	8	14	15					21	24
Option - # beamlines commissioned	8	32	64	112	120					168	192

Figure 5-4. Beam availability at NIF with a pause in construction at 120 beams.

5.2 SNL – Z Refurbishment/ Reduced NIF

SNL proposed to DP a two-part approach to meeting the requirements of the HEDP Program in support of SSP:

- Plan and execute the deployment of NIF to maximize needed data, and minimize programmatic costs and risks by addressing final configurations with fewer than 192 beams; and

- Refurbish the Z Machine at SNL and utilize it fully to provide HEDP data, this decade and beyond, to support LEPs and SFI resolution, the Secondary Certification Campaign, the Dynamic Materials Campaign, the Nuclear Survivability Campaign, and the ICF Campaign (for high-yield fusion capsule designs and to support the NIF Project).

SNL recognizes and acknowledges the important role of NIF in the SSP, but states that the final scope, deployment schedule, cost baseline, and impact on the balance of the SSP have not been fully established. They further state that the final configuration and deployment schedule of NIF should maximize the benefits to SSP at affordable costs and, therefore, assert that a subset of the current baseline should be identified as the “final configuration.” While advocating to proceed in a manner that would not preclude completion to 192 beams, SNL recommends that deployment beyond this "final configuration" be contingent on a cost-benefit argument related to SSP needs and requirements.

SNL states that, as for any large, complex project, significant cost and performance risks exist in meeting laser and physics performance requirements. Recognizing that the project has successfully addressed technical issues to date, and stating that risks at this point do not appear to preclude proceeding to some designated level of performance, SNL's concerns turn mainly to cost risks for completion and operations. Regarding the former, costs of significant ICF Program activities required to facilitate NIF (i.e., capsule cryogenic system and the diagnostics) have been assembled, but not yet reviewed. This adds uncertainty to the cost of full-NIF deployment. Operations costs need further clarification and resolution. A NIF operations cost model has been developed,[24] and the relationship of these operations costs to the historic (10-15 percent of capital costs) for large science facilities has been reviewed.[25] The NIF model is based on previous operations experience at large laser facilities at LLNL, where the experience showed operations costs to be in the range of 3-6 percent of capital costs. NNSA's judgment at this time is that there is up to a 50 percent uncertainty in NIF operations costs,[26] which gives Sandia concern. Operating parameters, such as shot rate, reliability of major components and systems, mean-time between significant maintenance events, etc., cannot be fully validated until a subset of the complete facility is available.

Therefore, SNL proposes a targeted deployment of NIF at less than the full 192 beams. Initial configurations of 48 and 96 beams should be carefully analyzed, as a new baseline with the decision based on the benefit to the SSP. A phased deployment should be planned with suitable performance milestones to validate laser systems performance (SNL agrees with LANL's suggestion that, at 48 beams, NIF demonstrate >75 percent energy and power [relative to Primary Criteria/Functional Requirements (PC/FR) third harmonic requirements] with >75 percent of beam through a 600-micron diameter pinhole), weapons physics and ignition proof-of-physics demonstrations (i.e., at 96 or 120 beams, demonstrate implosion and capsule physics for ignition), and cost-to-complete and operate. (Sandia realizes that 120 beams may be a more logical point for assessment, as it allows both more symmetric implosions and greater diagnostic capability (see Appendix E).) When targeted deployment is reached, an external review should be conducted to determine the cost-benefit to the SSP in proceeding to the originally planned full configuration of 192 beams.

The second part of the SNL proposal addresses further investments in pulsed power to provide "balance and diversity in the HEDP Program." The Omega, Atlas, and Z facilities will provide the primary capabilities to address HEDP-

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[24] U.S. NNSA, Office of the National Ignition Facility Project, Washington, DC.
[25] Ibid.
[26] Ibid.

related LEP and SFI needs during this decade. In particular, SNL advocates that the Z Machine provides unique capabilities to NNSA in SSP and basic sciences, complementing laser-based facilities. While laser systems provide precise pulse shaping, high-radiation temperature, and ultra-high-pressure experimental conditions, pulsed-power machines, such as Z, provide experimental environments for radiation effects (x-rays), dynamic material properties, and for driving larger-area, longer-time tests. The Z Machine has produced x-ray power and energy of >200 TW and 1.8 MJ, respectively, pressures of 2.5 Mbar in aluminum isentropic-compression experiments (ICE), and accelerated flyer plates to velocities of 21 km/s.

Therefore, SNL proposes refurbishment of the current 15-year-old Z Machine to increase the current delivered to wire-loaded arrays from 20 to 26 MA, and to increase pulse shape and width control for increased precision and reproducibility. The preliminary cost estimate for this refurbishment is $60 million in capital funds, and it could be completed by FY 2005 to support identified LEP needs. Refurbishment of Z would take place within the existing building and have minimal impact on availability of the current machine.

Performance enhancements would further enable access to weapons physics regimes of interest to the HEDP Program, such as radiated energy to 3 MJ; x-ray power to 350 TW; temperatures for weapons and ICF physics to 250 eV and 205 eV, respectively; ICE pressures to 10 Mbar in aluminum; flyer plate velocities 40-43 km-s^{-1}; and in-band energies (1 keV/5 keV/8 keV) to 700 kJ, 350 kJ, and 30 kJ, respectively. With associated increases in RTBF funds SNL anticipates achieving full machine utilization, increasing to a shot rate of 400 per year, as compared to the present funding-constrained rate of 180 per year.

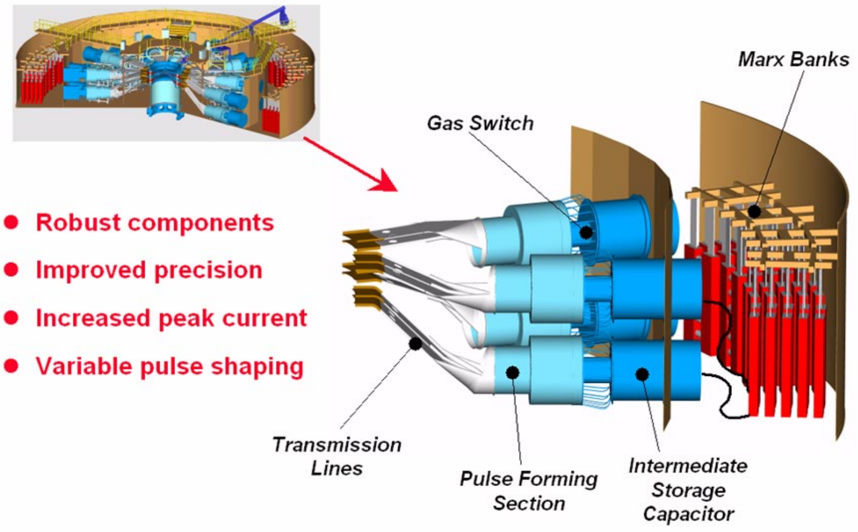

Figure 5-5. Performance enhancements would be obtained from the refurbishment of Z at SNL.

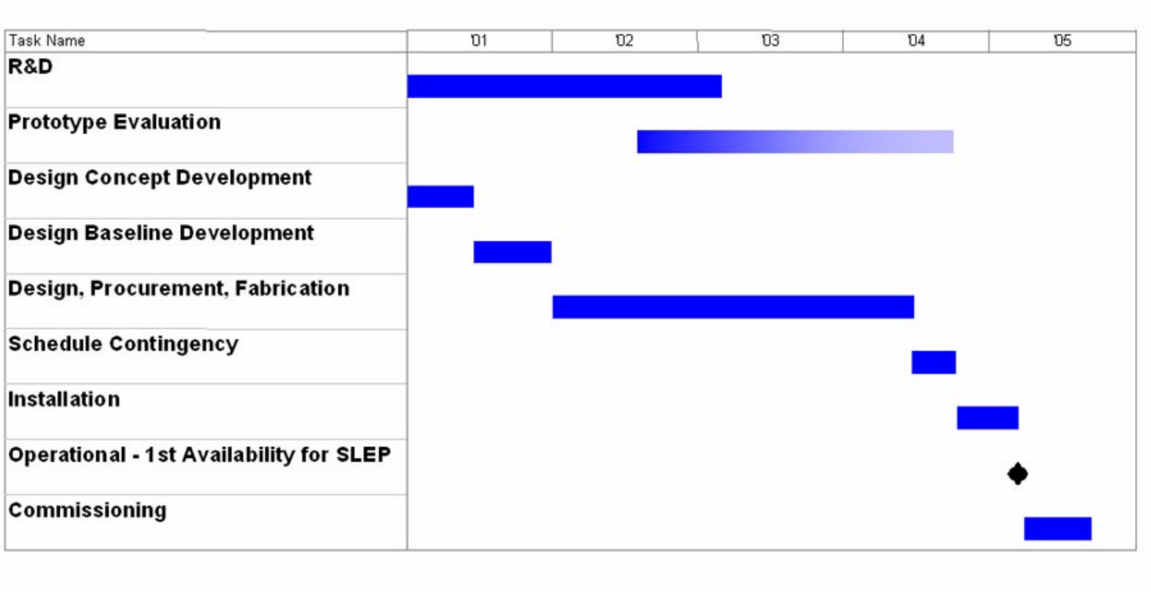

Figure 5-6. Proposed Z refurbishment schedule.

5.3 LANL – NIF Engineering Demonstration/Z Refurbishment

LANL proposed to DP two alternatives to the current HEDP Program:

- An engineering demonstration with associated milestones for NIF after commissioning the first cluster (48 beams), and
- A formal evaluation (mission need, conceptual design, cost estimate, etc.) by DP of refurbishing the Z Machine at SNL.

The first proposal to conduct an engineering demonstration has as its objective validating the integrated laser system performance, cost-to-complete, and projected operating costs of NIF. Details to be addressed in such a demonstration would include:

- Validate the performance of the final optics assembly, including relevant issues such as laser damage levels, conversion efficiency, ghost reflections, phase-plate operation, etc.;
- Validate single-beam performance, including energy per pulse, pointing and focusing specifications, and stability;
- Evaluate data from initial laser commissioning, to reduce risk in cost-to-complete;
- Evaluate data from early laser operation, to reduce risk in TPC and justify projected operating costs; and
- Evaluate data from early operation, to enhance confidence in ultimate shot rate, reliability, availability, and maintainability.

LANL suggested the following milestones:

- Demonstrate as-built laser system performance of >75 percent energy and power (relative to PC/FR third harmonic requirements) with >75 percent of the beam through a 600-micron diameter pinhole; and

- Utilizing data and operations models developed during early deployment and information gathered during commissioning of the first 48 beams, project ultimate NIF laser system shot rate and associated operating costs.

These laser performance milestones were agreed to, in principle, by the three laboratories and DP. Milestones of this type will be incorporated into the NIF Project baseline.

The second part of the LANL proposal advances the case for evaluating the potential of refurbishment of Z Machine to supply timely weapons physics data for upcoming LEPs, because NIF availability for weapons physics experiments (96 beams circa FY 2007 and full capability of 192 beams circa FY 2009) is not consistent with current SSP needs and requirements. LANL recommends a DP review of the physics breakpoints that could be achieved with a refurbished Z Machine, as well as a project review of SNL-proposed capital and operating costs. Assuming favorable results, LANL recommends that a refurbished Z Machine be added to the baseline HEDP Program.

5.4 Summary of Alternatives Studied

To provide both programmatic impact and cost information for proposed alternate NIF deployment scenarios, NNSA chose to study similar NIF alternatives for both the HEDP Study and the NIF Project. The NNSA defined the following set of HEDP Program alternatives for study, based on laboratory input (see Appendix J):

1. NIF – single cluster only (48 beams);
2. NIF – 96 beams;
3. NIF – 120 beams;
4. NIF – 96 beams, 3 year pause to evaluate performance and conduct tests;
5. NIF – 120 beams, 3 year pause to evaluate performance and conduct tests;
6. Addition of refurbished Z to the current HEDP Program baseline;
7. Addition of refurbished Z to 1)-5) above;
8. NIF – accelerated deployment schedule (“optimum”); and
9. NIF – addition of project milestones.

DP tasked the NIF Project to estimate the cost of the alternative deployment options to the current, September 2000, approved baseline (192 beams, to be complete in FY 2008, at a cost of $3,499 million). In preparing deployment options, DP guidance (see Appendix I) was to complete the full beam-path infrastructure and place all vendor-sensitive procurements (primarily large optics). LLNL generated schedule and cost estimates for a 192-beam optimized project schedule; 120 beams, 3-year pause, then complete; 96-beams, 3-year pause, then complete; and 48-beams, 3-year pause, then complete. The optimized project schedule (Figure 5-1) would allow completion of the 192 beams in FY 2006, but would require greater investment earlier in the Project.[27] For the other deployment options, a three-year pause translates into a five to six-year overall delay due to organizational factors (rebuild and ramp-up of project team), procurements, and re-entering the budget cycle, essentially moving project completion to the FY 2013-14 timeframe. Each of these later deployment options (Figures 5-2, 5-3, and 5-4) results in significant added total project costs.[28]

The programmatic impacts of stopping NIF construction at 48, 96, or 120 beams (along the current baseline) were assessed in the HEDP Study; the Project costs associated with terminating the current baseline at those points may be determined from the results of the 3-year pause alternatives.[29] Thus, both cost and program impact information is available for the HEDP alternatives identified above. The laboratories and the NNSA agreed that the set of alternatives listed above was an appropriate set to examine.

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[27] Ibid.
[28] Ibid.
[29] Ibid.

CHAPTER 6

Analysis, Findings, and Recommendations

Analysis, Findings, and Recommendations

DP has analyzed the baseline HEDP Program and the alternatives presented by the NNSA national laboratories. Findings and recommendations, resulting from the study, have been developed by DP and include, but are not limited to, input from the individual study panel members and senior laboratory and DP managers who participated in the study. The majority of information examined during the study dealt with classified weapons physics that is performed now and will significantly expanded, as NIF becomes operational. While that classified information is not explicitly presented in this unclassified report, it drives the analysis, findings, and recommendations in this report.

6.1 Analysis of the HEDP Baseline Program and Proposed Alternatives

Pulsed-power and high-power laser facilities produce complementary conditions. While there is similarity in the type of experiments that can be conducted, each type of facility produces unique conditions for HEDP experiments. Laser facilities typically are more suitable when high powers, high energy densities and precise spatial and temporal control of the delivered energy are required. Pulsed-power machines have produced record amounts of x-ray energy and are useful when high x-ray fluences, larger areas, and longer times are needed. Z experiments have addressed important weapons physics, weapons effects, and basic science questions, particularly in the materials area. Similarly, Omega, and Nova before it, have addressed important weapons physics issues, and enhanced the confidence in achieving ignition, and studied a variety of basic science questions. Laser experiments have demonstrated many scientific firsts, such as award-winning measurements of the EOS of deuterium. DP has found that these complementary capabilities are necessary to ensure the health of the HEDP Program, especially in the near term before NIF is operational.

NIF will be qualitatively and quantitatively different from Omega and Z. NIF will be able to produce energy densities approximately twenty times greater than any other facility. This will significantly increase the ability to access weapon-like conditions and will facilitate the study of issues affecting an aging and refurbished stockpile. The details of how NIF compares to Omega and Z are complex, because the metrics for comparison differ from issue to issue and from experiment to experiment. A number of such comparisons were considered in this study.

DP drew on the results of this study in reaffirming that NIF is needed. The reasons for this conclusion are as follows. First, NIF will enable a major increase in capability that will allow laboratories' scientists to probe weapon-performance behavior in regimes previously inaccessible. Second, NIF represents the culmination of almost thirty years of research and several tens of thousands of experiments in high-energy-density physics, using high-power, solid-state lasers. High-power lasers have proven their ability to execute a wide variety of experiments in different technical subfields, required to validate advanced simulation software. Third, NIF is unique in that it may achieve ignition. This will be a visible and important achievement, and will provide the only means known to access weapon-like thermonuclear-burn conditions in the laboratory. Fourth, the HEDP Program has a proven track record in attracting top talent to the national laboratories. NIF and the ignition challenge will continue this tradition.

The ignition goal is important for DP for several reasons. First, a laboratory ignition source is the only known means available to examine weapons issues related to thermonuclear burn in the laboratory. Second, ignition will require complex, difficult experiments that will challenge the abilities of the next generation of designers in a highly visible way, much as was done by experiments at NTS. Third, the ignition challenge is needed to attract top talent to the SSP. Fourth, as a difficult integral problem, ignition will be an important validation test for advanced simulation software. Finally, a number of speculative weapons-physics experiments involving ignition have been proposed. Further work is needed to determine the viability of these particular experiments. However, in common with other advances, ignition may provide benefits to the weapons program that have not yet been conceptualized, and that could be critical in the long-term sustainment of the nuclear deterrent.

The issue of the appropriate number of beams for the final NIF configuration was also considered in the HEDP Study. The laboratories generally agreed that 48 beams are inadequate. This is because the 48-beam configuration does not permit convergent implosions required by the weapons physics and ignition programs. In addition, with 48 beams, it would not be possible to achieve the physics conditions required for weapons physics, nor, for the conditions achievable, would it be possible to provide adequate backlighter beams for experimental diagnosis. Furthermore, in comparing 96 versus 120 beams, from a programmatic and cost/benefit perspective, stopping short of 120 beams makes little sense, assuming NIF meets its performance specifications and cost projections. This derives from a detailed analysis of the number of beams required both to irradiate targets and provide the backlighter beams necessary for experimental diagnosis.

DP has concluded that the 192-beam configuration for NIF is the correct goal for several reasons. First, 192 beams are needed to achieve ignition. DP believes that this is an important goal. Second, although LANL and LLNL differ in their views on this question, overall it appears the 192-beam NIF has important value for non-ignition, weapons-physics experiments, relative to its marginal cost. LLNL has developed a quantitative analysis that, in their view, shows that approximately two thirds of the value of the facility would be lost if the facility is configured with only 120 beams. LANL has not done a similarly detailed study, but asserts that this number is closer to twenty percent. Furthermore, LLNL assesses that approximately 80 percent of the marginal value of 192 beams is derived from non-ignition weapons physics. Finally, the full value of NIF as a tool to attract talent and validate advanced simulation codes will not be realized if the Project is limited to fewer than 192 beams.

The laser components for 120 beams will have been procured at the time when first cluster (48 beams) is completed. Therefore, it should also be noted that, if circumstances change, as long as a minimum of 120 beams is desired, it is possible to revisit these conclusions at any time through completion of the first cluster (48 beams). In particular, under all NIF alternatives considered, the Project baseline is unchanged through FY 2004.

The above discussion pertains to ignition and weapons physics, which are the two primary areas of HEDP Program activity. The roles of NIF and other facilities in the HEDP mission areas of weapons-effects testing, high-yield assessment, and basic science were also considered in this study. Z and Saturn are the primary DP capabilities for weapons-effects testing. The proposed refurbishment of Z would likely benefit the effects testing program. This will be considered in greater detail as part of the assessment of a refurbished Z. Although NIF will contain facilities for performing weapons-effects experiments, such experiments do not represent a major fraction of NIF's anticipated use. Correspondingly, the use of NIF for weapons effects was not examined in detail in this study.

As described in Chapter 3, the HEDP Program supports activities aimed at assessing the feasibility of high-yield fusion – the next step beyond ignition. Most HEDP Program activity in this area involves the Z accelerator, where approximately 25 percent of the available facility time is devoted to this topic. The assessment of a refurbished Z will include an assessment of its impact on this activity. There are speculative concepts for high yield at NIF involving the use of short-pulse lasers (the "fast igniter"). Based on the above work and physics results from NIF ignition experiments, the HEDP Program could determine options for a future high yield facility in the 2008-2010 timeframe.

Advancing the field of high-energy-density science is a mission goal for the HEDP Program. NIF, Omega, and Z contribute to this goal. With its ability to probe matter under extreme conditions, NIF is expected to generate major scientific advances of interest to both DP and the broader scientific community. Ignition is a major factor in this discussion, but there are others. An example is laboratory astrophysics, which has been explored on HEDP Program facilities. This has generated interest in the scientific community. Major breakthroughs are expected to play an important role at NIF, fulfilling its stewardship mission. An example of a breakthrough in an HEDP facility is the isentropic compression technique, a multi-laboratory experimental effort recently demonstrated on the Z accelerator. This technique, conceived only a few years ago, is now providing important data to the SSP.

As a final point, the analysis found that the refurbishment of Z appears to offer significant new opportunities in materials science, weapons effects, and other areas.

In summary, the HEDP Program, based on the triumvirate of NIF, Omega, and

Z provides a technically robust path forward for this component of the SSP.

6.2 Findings

DP has determined one principal finding and several major findings. These, as well as associated detailed supporting findings, are summarized below.

Principal Finding:

1. **A vital HEDP Program is an essential component of the SSP. The baseline HEDP Program, including completion of the 192-beam NIF, on the approved baseline, meets the SSP requirements and is the appropriate path forward.**

Specific DoD Concern:

2. In the current budget environment, full funding of the science portion of the SSP could put at high risk the ability of the NNSA to refurbish the production infrastructure and meet the current schedules for life extensions of the W76, W80, and B61.

Major Findings:

3. The different certification approaches of the laboratories all require enhanced understanding of weapon behavior embodied in the HEDP Program and the entire SSP. Some progress has been made toward development of quantitative metrics for stockpile assessment and certification.

4. Significant progress has been made in outlining a detailed experimental weapons physics program, to be conducted at NIF.

5. Ignition is an important goal for the HEDP Program, the SSP, and the national scientific community.

6. Alternatives to the current NIF Project baseline that include significant delays or pauses would have severe negative consequences for the NIF Project, the HEDP Program, and the SSP.

7. The proposed Z refurbishment shows promise for enhancing the HEDP Program, especially in the near term, but it cannot provide the same capabilities as NIF.

8. Balance and affordability of the HEDP Program, within the SSP, are significant concerns.

9. While more detailed analysis is required, the use of special nuclear materials at NIF may be important to maximize the value of the facility to the SSP.

10. People are the most important asset of the NNSA. The HEDP Program and NIF play an important role in attracting, training, and retaining the outstanding talent who will serve as the next generation of stockpile stewards.

11. A truly national program to utilize NIF, which builds on the existing user base, is essential.

Detailed Supporting Findings:

1. **A vital HEDP Program is an essential component of the SSP. The baseline HEDP Program, including completion of the 192-beam NIF, on the approved baseline, meets the SSP requirements and is the appropriate path forward.**

1.1 *A strong HEDP Program is essential to the SSP.* Data in the high-energy-density physics regime are central to assessing the secondary phase of nuclear weapons performance. HEDP data also play a role in assessing certain aspects of primary performance. The HEDP Program provides experimental capabilities necessary to study these issues, thus, facilitating the creation of a trained cadre of scientists experienced in weapons design, diagnostic development, and experimental techniques. This will also support nuclear test readiness.

1.2 *A balanced HEDP Program that includes laser (NIF, Omega) and pulsed-power facilities (Z) is needed for SSP, now and in the future.* NIF will allow the HEDP Program to access regimes never before explored in the laboratory. This will provide the advanced understanding of HEDP required to support future assessment and certification. Omega and Z are the major experimental facilities required to support the program in the near term. In the future, they will also serve as primary staging facilities for NIF. Omega and Z each provide unique complementary capabilities. An example presented at the HEDP Workshop was the equation of state for deuterium. Recent pulsed-power results in this area may differ from those obtained using lasers and may shed light on this important question. Diversity of facilities and personnel involvement is important to ensure that the tools and the cadre of experts ultimately responsible for certification decisions are sharpened and improved over time.

1.3 *Although the full NIF will not be available during the development and initial production phases of the LEP's for the W76, B61, and W80, it is expected to be of importance in their continued certification.* Omega and Z will be available for these programs and should enhance confidence through code validation and resolving physics uncertainties. After refurbishment of these weapons is complete, advanced SSP capabilities, such as NIF, will be important for maintaining confidence in these weapons in the longer term. NIF will become operational well before completion of the full facility (see Appendix E), and will likely play a role in assessing questions that may arise from these refurbishments. NIF's role is most important in the future when certification without testing becomes more difficult than it is now, because of the passage of time since the end of nuclear testing.

1.4 *While NIF and other HEDP facilities are important tools in the certification kit, they cannot do the whole job.* The entire suite of capabilities planned for the SSP will be needed to develop the required fundamental understanding of weapon behavior. The maintenance of a reliable production capability is also essential to success of the SSP.

1.5 *NIF and other HEDP facilities (like other major science facilities) provide unparalleled opportunities for creative inquiry at the cutting edge of many scientific fields.* Fundamental programmatic and scientific breakthroughs are expected with these machines. The most exciting results to be obtained from them cannot yet be predicted. An example of this, shown at the workshop, is the isentropic compression technique, recently developed on Z. Several years ago, this revolutionary technique, which is now addressing significant materials issues for the SSP, did not exist. Such breakthroughs will be important in certifying the stockpile in the long term, in the absence of nuclear testing.

1.6 *HEDP understanding is of significant importance to the stewardship activities of our nuclear-weapon allies, France and the UK.* Written statements from France and the UK were received regarding their stewardship programs and the role of HEDP within them (see Appendices F and G). As in the U.S., the study of high-energy-density physics is an essential component of the stewardship programs of both of these countries. Both cite the value of HEDP in attracting top-class talent. HEDP is a major underpinning element of the CEA weapons program. According to the CEA, success in designing ignition targets for the 240-beam LMJ laser will be *the* metric used to judge the next generation of designers in France. The UK must have access to HEDP facilities. The UK plans to make use of NIF. This will be facilitated via a shot rate enhancement program. In conjunction with the NNSA and the laboratories, the UK is also examining the use of other facilities, including Omega and Z.

2. **Specific DoD Concern: In the current budget environment, full funding of the science portion of the SSP could put at high risk the ability of the NNSA to refurbish the production infrastructure and meet the current schedules for life extensions of the W76, W80, and B61.**

2.1 *Strong concerns were voiced during this study regarding the health of the manufacturing complex.* DP must ensure support for an adequate manufacturing base in both the near and long term. In the case of a constrained budget, the increased funding required for NIF and other components of the campaigns results in stress on the production complex.

2.2 *Under a constrained budget, needs within the Research, Development, and Simulation program, includ-*

ing the extended and increased funding profile associated with NIF, result in stress on the production complex and the Life Extension Programs. The original plan for the Stockpile Stewardship Program involved the completion of major facilities, such as NIF. This was to be followed by investment in other stewardship capabilities. As the program has evolved, needs for investment in the production complex to support refurbishments have been identified.

2.3 *Overall, NNSA must continue to examine the overall SSP and ensure that a safe, secure, and reliable stockpile is maintained in a sound and cost efficient manner.* Both refurbishment and research, development, and simulation activities are essential for a successful program. The balance among them must be carefully managed. The HEDP Program is obviously not the only issue in this ongoing assessment. The funding tensions within the SSP belong to all participants and corporate solutions must be found.

3. **The different certification approaches of the laboratories all require enhanced understanding of weapon behavior embodied in the HEDP Program and the entire SSP. Some progress has been made toward development of quantitative metrics for stockpile assessment and certification.**

3.1 *Maintaining the safety and reliability of the nuclear weapons stockpile indefinitely, without nuclear testing requires, major advances in scientific understanding of nuclear weapons behavior.* The SSP must identify and pursue those endeavors required to enable continuing certification of the weapons in the stockpile. The specific program of work, including scientific research and tool development, follows from the approach that the laboratories take in weapon certification.

3.2 *The laboratories, particularly LANL and LLNL, employ different approaches for present certifications.* For certification of the nuclear explosive package, two approaches to stockpile assessment and certification have been raised in this study. Both viewpoints share a common requirement for better science, but they lead to different emphases in the specifics of what science must be pursued. In either case, near-term assessment and certification activities generally rely on nuclear designers familiar with as-built and tested designs and, to a large degree, will be based on their experience and confidence in empirically "normalized" weapon performance models. More basic scientific understanding will be necessary for long-term success of the SSP. In particular, the long-term approach should increase confidence in the stockpile and provide the capability to respond to the increasingly broad range of issues (both planned and unplanned) that will arise in maintaining the aging stockpile.

3.3 *Quantitative standards, derived from a detailed scientific understanding, would improve confidence in certification of the stockpile.* LANL and LLNL are making progress in this area. LLNL has formulated an overall program aimed at quantifying uncertainties that leads to quantitative assessment and certification standards. LANL has shown an example of the certification process for a particular system that employed a statistical approach. Further analysis of this type will be essential in formulating a long-term assessment/certification strategy for the NNSA.

4. **Significant progress has been made in outlining a detailed experimental weapons physics program, to be conducted at NIF.**

4.1 *LLNL and LANL presented information on their plans for weapons physics experiments on NIF, Omega, and Z.* LLNL has proposed an extensive suite of weapons physics experiments to be potentially performed at NIF, Omega, and Z, derived from their view of the quantitative requirements for assessment and certification. LLNL's quantitative standard is that the margin exceeds the uncertainties for a set of known weapon failure modes. The LLNL presentations included detailed information as to how NIF would quantitatively assess these uncertainties and thereby help reduce them to a tolerable level. This set of talks was detailed, comprehensive, and innovative. LANL considered a subset of their proposed weapons physics program and presented a clear discussion of how Omega, Z, partial, and full NIF compare in executing a particular set of experiments.

4.2 *A significant portion of NIF weapons-physics experiments, proposed to be conducted at NIF, will not require ignition, but will require the full 192 beams, because of symmetry considerations, power-on-target, back-lighting requirements and other issues.* LLNL's proposal includes an extensive discussion of non-ignition NIF weapons physics experiments that would require 192 beams. Their analysis includes target drive conditions and experimental requirements such as diagnostic resolution and the number of backlighter beams needed to obtain quality data. Inclusion of experimental requirements was an important step and influenced discussions about the relative value of a given number of NIF beams to HEDP/SSP. While portions of this analysis have been discussed elsewhere, the workshop was the first time that the entire package had been brought together. The discussion underscored the technical importance of a 192-beam NIF to stewardship, independent of ignition.

4.3 *Peer review of the experimental programs proposed by the laboratories is needed and would benefit the HEDP Program.* In particular, the quantitative link between experiments and the ability to assert certification to requirements should be reviewed.

5. **Ignition is an important goal for the HEDP Program, the SSP, and the national scientific community.**

   5.1 *Ignition will be an important tool because it will provide a design and certification test challenge for designers, similar to what existed when weapons were nuclear tested, and will provide a means of maintaining scientific excellence and "certifying the certifiers."* Conditions in ignition capsules are not identical to those within a weapon, but the challenge of solving a difficult, visible, integral problem will be important in maintaining a robust nuclear design program.

   5.2 *The quest for ignition provides the intellectual challenge and excitement necessary to recruit and retain talented people.* The excitement of the ignition goal is an essential ingredient to attract, train, and retain top-quality talent for stockpile stewardship. With NIF as a national user facility, university scientists interested in fusion energy will be drawn into the weapons program by this "grand challenge."

   5.3 *Although LLNL, LANL, and SNL all find ignition to be an important national goal, they differ in their assessments of its importance to understanding weapons phenomena and the pace at which this goal should be pursued.* In terms of direct impact on the stockpile, LANL believes that ignition is a valuable "integral" problem and designer training exercise but that "near-ignition" integrated experiments could be of similar value. In the LLNL view, ignition experiments provide certain basic physics data and code validation, as well as challenging integral problems. LLNL estimates that approximately twenty percent of the marginal value of 192-beam NIF is attributable to the uses of ignition. The SNL view of ignition, in the area of weapons effects, is that NIF ignition at the 30-40 megajoule level is of limited utility for warm x-ray effects testing, due to the short x-ray pulse-width and neutron background.

   5.4 *The goal of ignition is of interest to the broader scientific community.* Professor Richard Petrasso (Massachusetts Institute of Technology) stated at the HEDP Workshop that the challenge of ignition was the primary reason graduate students are attracted to his research program. Achievement of ignition would be widely recognized and applauded. The Inertial Fusion Energy Program, within the DOE Office of Fusion Energy Science, is predicated upon a demonstration of ignition at NIF.

6. **Alternatives to the current NIF Project baseline that include significant delays or pauses would have severe negative consequences for the NIF Project, the HEDP Program, and the SSP.**

6.1 *Addition of a pause, or pauses, to the current NIF baseline would increase project cost and risk, and would jeopardize the successful completion of the Project, with concomitant impacts on the SSP.* The NIF Project baseline is the slowest possible that still maintains Project momentum. Compared to the cost of the project, there is relatively little money to be saved by stopping the Project at an intermediate level, because the high cost of the basic facility and its infrastructure. To subsequently restart the Project and continue it to its conclusion would be considerably more costly than not stopping at all. Addition of a pause to the current baseline is not cost effective and would increase, not decrease, project and programmatic risk. The only other alternative is acceleration of the current baseline, which is not the preferred option, given the financial constraints on the stewardship program and the desire to mitigate technical risk.

6.2 *Failure of the NIF Project could decrease the viability of LLNL as an institution, a risk that has important implications for the long-term nuclear security of the nation.* Major delays in the NIF baseline could severely damage LLNL, as an institution, which is an outcome the nation cannot afford.

6.3 *The full benefits of NIF to the SSP will not be realized if the project is limited to less than 192 beams.* The 48-beam NIF was found to be inadequate for the SSP. In comparing 96 beams versus 120 beams, from a programmatic and cost/benefit perspective stopping short of 120 beams makes little sense. This is derived from a detailed analysis of the number of beams required to both irradiate targets, while simultaneously providing the backlighter beams necessary for experimental diagnosis. LLNL showed, by a quantitative analysis, that, in their view, approximately two thirds of the value of NIF would be lost if the facility is terminated at 120 beams. LANL has not conducted a similarly detailed study, but asserts that the reduction in value is closer to twenty percent. The difference in the laboratories respective views is due to their differing perspectives on the importance of ignition and the value of 192-beam experiments for weapons physics.

6.4 *Insertion of additional mileposts in the NIF Project, near the time that 48 beams are operational, would provide an important opportunity for review and would benefit the HEDP Program.* The inclusion of additional mileposts near the time of 48 beams is a significant aspect of the alternatives submitted by LANL and SNL. As demonstrated by ASCI, there is merit in identifying useful mileposts, to be confirmed by external review, along the current baseline path. These mileposts may involve the NIF Project, the HEDP Program, or both, and can be crafted in such a way as to strongly encourage more cooperation among the three weapons laboratories. Portions of the proposed LANL and SNL mileposts relate to validation of laser performance. As part of their alternative, LANL proposed specific laser performance milestones for the NIF Project. Milestones of this type have been accepted by DP and the three laboratories and will be incorporated into the NIF Project via the formal baseline-change-control process.

6.5 *The long-term ability of the HEDP Program to address stockpile stewardship questions would be degraded by any further delay in constructing NIF.* Rigorous underpinning for advanced modeling is needed, as soon as possible, to assess the stockpile and to train the new stewards before the last of the scientists and engineers with nuclear testing experience retire. The stockpile is scheduled to undergo changes before NIF is completed. Further delay in NIF would increase the uncertainty in assessing the effect of those changes on weapons performance. In the future, NIF is expected to play an important role in the event that new weapons designs are needed.

6.6 *A strong project management team and system are in place at LLNL, with appropriate review mechanisms, maximizing the probability that the NIF Project will succeed.* Although this study did not formally review the NIF Project, it appears that LLNL has demonstrated that it now has a strong management team and project management system in place. The NIF Project has been reviewed extensively in the last two years, and those expert reviews have concluded that the Project is now robust and should proceed forward. Demonstrated performance by the LLNL team, as well as intrusive, external semi-annual reviews are essential to maintaining the credibility of the NIF Project.

7. **The proposed Z refurbishment shows promise for enhancing the HEDP Program, especially for the near term, but it cannot provide the same capabilities as NIF.**

7.1 *The Z accelerator provides important capabilities for the HEDP Program in the areas of weapons physics, high yield assessment, weapons effects testing, and basic science.* Numerous collaborative experiments, on the present Z, by weapons personnel from LLNL and LANL, demonstrate its value as an important HEDP facility, especially during the extended time before NIF experiments begin. Z has demonstrated outstanding progress. Recent work on material properties is a particularly good example. The Beamlet laser, which was built as a scientific prototype for NIF, has been relocated from LLNL to SNL to serve as a backlighter. It will increase considerably the experimental capability of Z. The proposed Z refurbishment largely involves replacement of worn components and would result in an approximate 50 percent increase of the x-ray energy.

7.2 *A recent, external review of the Pulsed Power Program at SNL,*[30] *chaired by Richard Garwin, found that excellent progress has been made, but additional funds are needed to ensure that Z is optimally utilized and properly maintained. This review panel also recommended that the Z refurbishment option go forward.*

7.3 *While refurbished Z cannot access the same HEDP parameter-space regime as NIF, it shows promise as a cost-effective addition to the HEDP Program.* The value of a refurbished Z indicates that it may well be worth its estimated price of $60 million. DP will examine this issue further.

8. **Balance and affordability of the HEDP Program, within the SSP, are significant concerns.**

8.1 *The large cost of the NIF Project has led to significant stress in the SSP that must be thoughtfully and carefully managed.* LANL and SNL concerns involve the cost/benefit ratio for NIF within the HEDP Program and the SSP. In particular, their concern is that the operating and user costs of the full NIF could be so large that, under a constrained budget scenario, NIF will drive out the other smaller complementary HEDP facilities and, with them, the diversity and complementarity important to a healthy HEDP Program. SNL and LANL are also concerned that NIF costs may negatively impact other programmatic activities at their laboratories that are required for certification of the stockpile.

8.2 *NIF operating costs are a high-visibility issue that will require ongoing attention from the NIF Project, DP, and the laboratories.* The NIF Project addressed the issue of NIF operating costs in this study, and it will continue to be examined as part of the semi-annual NIF Project review process. A detailed review of operations costs will be scheduled after first light is achieved at NIF, in approximately 2004.

8.3 The approach of each laboratory to HEDP reflects their respective approach to and role in certification.

8.4 *There is significant disagreement among LANL, LLNL, and SNL regarding balance within the HEDP Program and between the HEDP Program and the remainder of the SSP.* Some of this can be ascribed to the existence of various views and various approaches to difficult problems (i.e., the creative tension). These different views and approaches are desirable and needed. However, while the laboratories cooperate well in many technical

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30. "Pulsed Power Peer Review Committee Report," Richard Garwin, chair, July 2000.

areas, there is an unhealthful level of discord among the laboratories. Most of this is traceable to concerns over funding. It is important to note that this could damage the SSP. While the NNSA derives the benefits of the multi-laboratory system, it must also manage the conflicts that are inherent in that system. It should be noted, the laboratories agree that a solid HEDP Program that includes a major portion of the planned NIF is needed. Excessive argument on this question can be misleading to outside observers, as it may imply that the scientific and technical challenges presented by the SSP are not as great as the laboratories and NNSA agree they are. Excessive argument also can erode the confidence the NNSA's military partners have in the ability of the laboratories to conduct the SSP. In both cases, such arguments may ultimately put the stockpile at risk. This point was emphasized by a number of study participants external to DP.

9. **While more detailed analysis is required, the use of special nuclear materials at NIF may be important to maximize the value of the facility to the SSP.**

9.1 *The possibility of conducting experiments using special nuclear materials in experiments at NIF and on the Z machine should be explored further, consistent with technical and resource considerations, legal requirements, and safety and environmental regulations.* LLNL has described a number of promising experiments involving special nuclear materials at NIF. DoD participants in the study were strongly supportive of this. Some preliminary comments on the use of SNM on Z were also provided. DP will examine this possibility further, in a manner consistent with all legal and environmental requirements.

10. **People are the most important asset of the NNSA. The HEDP Program and NIF play an important role in attracting, training, and retaining the outstanding talent who will serve as the next generation of stockpile stewards.**

10.1 *The long-term success of stockpile stewardship depends on attracting and retaining highly qualified individuals.* This requires that the program be exciting, important, and challenging, with facilities and capabilities at the frontier of science, computing, and experimentation. NIF will contribute significantly to recruiting and retaining top scientists to the labs. One of the most important applications of NIF is that it will provide the opportunity to conduct a set of complex, difficult, high-risk experiments that will challenge the abilities of the next generation of nuclear designers in a highly visible way, much as was done by experiments at the NTS. From the personnel perspective, NIF is important in maintaining the stockpile and, more broadly, to sustaining the nuclear deterrent.

10.2 *A successful NIF and a vigorous HEDP Program may contribute to reversing the observed negative trend in attracting highly talented individuals to the weapons program.* There is evidence that recruiting at DP facilities has become much more difficult. Without a clear vision of where NNSA is heading, including NIF, recruiting by the laboratories will suffer in quality and quantity. Some cultural shifts at the laboratories will be needed in order to develop a new generation of stewards who can certify the stockpile and be "certified" by HEDP and other SSP experiments.

10.3 *A viable HEDP Program, including NIF will encourage university presence in HEDP.* This will enable universities to produce newly trained individuals for employment in the weapons programs at LANL, LLNL, and SNL.

11. A truly national program to utilize NIF, which builds on the existing user base, is essential.

11.1 *DP must work closely with the user community to make NIF a truly national facility.* A first draft of the NIF Governance Plan is due to DP by April 30, 2001. This plan must be developed with input from the entire NIF user community, including the national laboratories, universities, and other federal agencies, such as DoD. The plan must address issues, such as the method for allocating shot time at NIF and how the user group organization will function.

11.2 *The NIF basic-science user community is taking shape, as evidenced by the October 1999 workshop organized by Professor Richard Petrasso (MIT), the interim head of the NIF Basic Science Users Group.* There were more than 150 attendees, with representatives from universities, at the workshop. A wide variety of cutting edge experiments on NIF was discussed, and the 1999 workshop advanced the definition of the basic-science program at NIF.

11.3 *Further support from DP and the NIF Director is required for the NIF Basic Science Users Group to reach its full potential.* The NIF Director will need to create an organization to work with the user community, including the basic science user group. The university community will require support in order to use NIF and other HEDP facilities effectively. DP currently supports university activities in HEDP and this will likely need to be enhanced as NIF comes on line.

6.3 Recommendations

Principal Recommendation:

1. **DP recommends that the NNSA continue with the baseline HEDP Program, including Omega, Z, and the 192-beam NIF, including the goal of ignition.**

   This study concludes that the triumvirate of major facilities – NIF, Omega, and Z – is needed to support the HEDP Program and the SSP, now and in the future. NIF will be needed in the medium to long term for three principal reasons: 1) to study issues that can affect an aging or refurbished stockpile; 2) to advance critical elements of the underlying science of nuclear weapons that will play a major role in validation of advanced simulation codes; and 3) to attract and train the exceptional scientific and technical talent required to sustain the SSP, over the long term.

Major Recommendations:

2. **DP strongly recommends that the NIF Project continue along the current baseline and maintain the goal of completing the full set of 192 beams.**

   This is recommended for four reasons. First, programmatically, this study re-emphasized that the full benefits of NIF, as an experimental facility and an attractor of talent, will not be realized if the project is limited to less than 192 beams. Second, the NIF Project is proceeding on a schedule that is limited by the available funding profile in a balanced SSP. Slowing the project further would increase project risk. It is important to the SSP, NNSA and the laboratories that NIF be a success. Third, the incremental cost of increasing from 120 to 192 beams is low. Finally, there will be time to revisit this issue in the future as experience is gained operating NIF.

3. **Semi-annual reviews of the NIF Project should continue. NNSA and its laboratories should work together to define mutually acceptable project and HEDP Program milestones to monitor overall NIF progress and encourage formation of a national program.**

   Intrusive, semi-annual reviews should continue to monitor all aspects of progress on the NIF Project, including operations costs. The value of major national, multi-laboratory milestones has been demonstrated by ASCI. Applying this concept to the NIF Project and the HEDP Program should be examined. A sensible time to complete an overall assessment of NIF will occur near the time of first cluster (48 beams). Laser-performance milestones of the type suggested by LANL will be incorporated into the NIF Project.

4. **NNSA should support the robust technical program that is required to meet the increasing challenges of the assessment and certification program that will arise due to aging, remanufacturing, and the discovery of design flaws within the stockpile.**

Quantitative metrics for assessment and certification should continue to be developed, to increase confidence in the stockpile.

As time progresses, in the absence of testing, assessment and certification activities that are driven by aging, remanufacturing, and the discovery of design flaws will require increasing extrapolations from the existing nuclear test archive. These extrapolations will require a sound, scientific understanding of weapons performance and reliability, which is a central element of the technical program that DP has been developing during the past several years.

5. **The weapons physics material presented by LLNL, at the HEDP workshop, forms a solid basis for further discussion and should be peer-reviewed in detail.**

   This set of presentations at the workshop is an important contribution to the SSP and should serve as a springboard for further discussions among the weapons laboratories on HEDP and quantitative methods for certification.

6. **The five-year planning process within DP and NNSA should be broadened and instituted as a permanent, ongoing, strategic planning effort used to aid DP, NNSA, and the laboratories in assessing program balance and managing the SSP at a top level.**

   A more systematic process to assess detailed budgetary and technical trade-offs within the SSP is needed. This strategic planning effort should include all aspects of the program, not just HEDP. DP has invested a great deal of effort, during the past five years, in determining the correct set of capabilities to support science-based stewardship. In the event that budget or other reasons preclude the execution of major elements of the planned HEDP Program or SSP, a comprehensive rethinking of the entire stewardship program will be necessary, because the development of the required science and technical base will no longer be possible.

7. **The proposed refurbishment of Z shows promise and should be formally considered by the NNSA for inclusion in the baseline HEDP Program.**

   The refurbishment of Z should be reviewed from both a programmatic ("mission need") and project management standpoint. These reviews should quantify the benefit of a refurbished Z to the HEDP Program and consider the viability of the proposed scope, schedule, and cost of the Z-refurbishment project.

8. **The possibility of using SNM in experiments at NIF and on Z should be examined, consistent with technical considerations, resource requirements, legal requirements, and safety and environmental issues and regulations.**

   The NNSA is committed to making a decision on the use of SNM in experiments at NIF, no later than January 1, 2004. The laboratories' preliminary calculations, shown at the HEDP Workshop, should be extended and reviewed as part of the decision-making process. Should NNSA decide to propose such experiments, appropriate National Environmental Protection Act (NEPA) action will be taken, analyzing the reasonable, foreseeable environmental impacts of such experiments. The use of SNM on Z will also be examined in a manner that is fully consistent with all regulatory requirements.

9. **The draft NIF Governance Plan should be developed for comment by April 30, 2001, as per recent direction from the NNSA.**

   The NIF Director should work closely with DP, the NNSA and other laboratories, including all of the ICF Program laboratories, on this important task. The NIF Director is strongly encouraged to examine other NNSA and DOE Office of Science user facilities as models for the plan.

10. **The NNSA should develop a focused recruiting program, based on NIF and other major HEDP/SSP capabilities.**

    The NNSA should examine the feasibility of executing this program jointly, with other interested federal organizations.

6

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APPENDICES

APPENDICES

Appendix A – Workshop Agenda

HEDP Workshop Agenda
SNL/CA 30 January – 2 February

TUESDAY, 30 JANUARY

MORNING – NNSA OVERVIEW & LAB CERTIFICATION APPROACHES

8:00-8:05 am	Introduction of Gen. John Gordon	Tom Hunter (SNL)
8:05-8:20	Opening Remarks	Gen. Gordon (NNSA)
8:20-8:35	Introductions & Expectations	D. Crandall (NNSA)
8:35-9:00	Overview Baseline & Alternatives	C. Keane (NNSA)
9:00-9:45	Certification Approach	M. Anastasio
10:00-10:15	*BREAK*	
10:15-11:00	LANL Wpns Prog. & Approach to Certification	S. Younger
11:15-11:50	Certifying the Stockpile without Underground Testing	T. Hunter
12:00-12:10	Nuclear Survivability Certification	J. Lee
12:15-1:15 pm	*LUNCH*	

AFTERNOON – NIF OVERVIEW & START OF LAB HEDP PROGRAM PERSPECTIVES

1:15-1:35 pm	LLNL Introduction	G. Miller
1:45-3:00	NIF Project View of Baseline & Alternatives	E. Moses
3:15-3:30	*BREAK*	

HEDP Baseline & Alternatives – LLNL Perspective

3:30-4:15	Primary Certification & HEDP	B. Goodwin
4:30-5:15	Constitutive Properties	B. Remington

5:30-6:15	Complex Hydrodynamics in Primaries	D. Rowley
6:30 pm	*ADJOURN*	

EVENING – WORKING DINNER FOR ALL WORKSHOP PARTICIPANTS

Pasta's Trattoria, 7 PM
4040 East Avenue, Livermore
925-456-3333
Cost: $30/Person (cash)
Directions may be obtained from Joan Bersie and Deb Rubin-Bice

WEDNESDAY, 31 JANUARY

MORNING – HEDP BASELINE & ALTERNATIVES – LLNL PERSPECTIVE (CONT.)

8:00-9:00 am	Secondary Certification & HEDP	R. Ward
9:15-10:00	Radiation Flow	J. Bauer
10:15-10:30	*BREAK*	
10:30-11:15	Opacities and Other Key Physical Data	P. Springer
11:30-12:15	Complex Hydrodynamics in Secondaries	T. Peyser
12:30-1:30 pm	*LUNCH*	

AFTERNOON – HEDP BASELINE & ALTERNATIVES – LLNL PERSPECTIVE (CONT.)

1:30-2:15 pm	Equation-of-State	R. Cauble
2:30-3:15	Novel Uses of Ignition	S. Libby
3:15-3:30	BREAK	
3:30-4:15	Experimental Requirements Summary	W. Hsing
4:30-5:15	LLNL HEDP for Weapons Summary	M. Anastasio
5:30 pm	ADJOURN	

EVENING

NIF Tour: This tour will start at the conclusion of the workshop talks. We will assemble the list of participants for this tour at the workshop.

Working Dinner for Study Panel Members and Senior Participants
The Jade Room, LLNL
Reception – 6:30 pm
Dinner – 7:15 pm

THURSDAY, 1 FEBRUARY

MORNING – HEDP BASELINE & ALTERNATIVES – SANDIA PERSPECTIVE

8:00-8:20 am	Introduction to Sandia Alternatives	T. Hunter
8:30-8:50	Sandia Alternatives	J. Polito
9:00-9:20	Pulsed Power Supporting the SSP	J. Quintenz
9:30-9:45	*BREAK*	
9:45-10:10	Secondary Certification and ICF Experiments on the Z Accelerator	K. Matzen
10:20-10:45	New Technologies for Nuclear Survivability Certification	J. Lee
10:55-11:20	Materials Dynamics Experiments on the Z Accelerator	J. Asay
11:30-11:45	Wrap-up	T. Hunter
11:45-12:15 pm	*WORKING LUNCH*	

AFTERNOON – HEDP BASELINE & ALTERNATIVES – LANL PERSPECTIVE

12:45-1:30	Executive Session	
1:30-2:10	Brief Outline of LANL Alternative Proposals	A. Hauer
2:20-3:20	Certification Methodology – A Case Study	B. Wilde
3:35-3:50	*BREAK*	
3:50-4:50	Contributions of HED Program to SSP	W. Krauser

5:05-6:05	Characteristics of HED Drivers Required	R. Chrien
6:20	*ADJOURN*	

EVENING

Working Dinner for Study Panel Members and Senior Participants
Buffet in Meeting Room, 6 PM
Cost: $25/Person (cash or check to Joan Bersie)

FRIDAY, 2 FEBRUARY

FURTHER INDIVIDUAL PERSPECTIVES & REVIEW SESSIONS

	Individual Perspective	S. Koonin (CalTech)*
8:00-8:30 am	NIF and Inertial Fusion Energy (Individual Perspective)	R. McKnight (DOE/SC/ OFES)
8:30-9:00	Target Physics Review (Individual Perspective)	D. Giovanielli (Consultant)
9:15-10:30	Basic Science on HED Facilities (Individual Perspective)	R. Petrasso (MIT)
10:30-10:45	BREAK	
11:00-12:15	Laboratory Perspectives & Review	
12:15-1:15 pm	LUNCH	
1:15-2:15	Laboratory Perspectives & Review (cont.)	
2:15-6:15	Panel Member Discussion & Writing Session	Panel
6:15 pm	ADJOURN	

*Presented on Thursday at 12:15 to 12:45, because of schedule conflicts.

Appendix B – Baseline High Energy Density Physics Program Description

High Energy Density Physics PROGRAM BASELINE
January 26, 2000

Mission Statement

The mission of the HEDP program is to provide the physics data and scientific understanding in the high energy density regime required to maintain the safety, security, reliability, and performance of the nation's nuclear weapons now and in the future without nuclear testing. The HEDP Program, in areas such as demonstrating fusion ignition, studying the feasibility of high yield fusion in the laboratory, and advancing basic scientific understanding, also supports broader national objectives.

Background

The overall HEDP Program includes a mix of experimental, theoretical, and computational activities in support of the Defense Programs (DP) Stockpile Stewardship Program (SSP). The HEDP program encompasses activities in the DP Campaigns, Readiness in Technical Base and Facilities (RTBF), and National Ignition Facility (NIF) construction. The HEDP program is closely coupled with the Accelerated Strategic Computing Initiative (ASCI) and Direct Stockpile Work (DSW). For purposes of the current HEDP/NIF study, however, we will not explicitly consider in detail ASCI or DSW funded activities. The validation of ASCI codes via experiments on HEDP facilities is of course included in the study, as is the total scope of computational activities within the Inertial Confinement Fusion (ICF) Program. The HEDP Program also draws on the nuclear test database and the broader scientific community.

Thus, for purposes of this study the HEDP Program baseline may be described as follows:

Program Requirements

a) Provide the scientific understanding and experimental capabilities (including diagnostics) as required by the SSP in order to validate codes, collect fundamental data for databases, and answer specific concerns about the stockpile. Specific physics regimes for HEDP experiments have been identified (within the Sec. 3158 report and elsewhere) in the following areas:

  - High temperature opacity of weapon materials.

- High pressure equation-of-state (EOS) experiments of weapon-relevant materials in the high-energy-density (HED) regime.

- Radiation experiments pertinent to the weapon regime.

- Complex compressible hydrodynamic experiments involving features such as gaps or grooves.

- Thermonuclear deuterium-tritium (DT) ignition experiments.

b) As mandated by the broader SSP, develop advanced radiation sources (including possibly high yield sources) for nuclear effects testing.

c) Provide facility time and access to the broader community so as to advance basic HEDP science.

Program Goals

The HEDP Program is oriented to achieve the following (not priority-listed) set of goals:

a) Ensure (in conjunction with the laboratories and other federal agencies) that the national scientific base in HEDP is adequate to support SSP.

b) Execute high energy density weapons physics experiments required by the SSP.

c) Develop advanced x-ray sources for nuclear weapons effects testing.

d) Attract, train and retain outstanding talent to the HEDP Program.

e) Maintain the U.S. position as the world leader in HED science.

f) Complete construction of the NIF Project and the Z-backlighter on the current cost and schedule.

g) Demonstrate ignition on NIF by 2010.

h) Develop options, in the 2008-2010 timeframe, for a next generation high yield facility.

i) Develop and fabricate the diagnostics and cryogenic systems required for NIF.

j) Develop the advanced laser and pulsed power technologies required for NIF and a potential next generation pulsed power machine.

k) Support broader national goals that require involvement from the DP HEDP Program.

Program Strategy Elements

i) **Weapons Physics:** The ICF Program, in conjunction with the other DP campaigns and DSW, executes the HEDP experiments required for the SSP. This involves experiments (many of them classified) in a wide variety of areas, including radiation flow, hydrodynamics, and material properties. NIF, Omega, Z, Trident, and Janus are heavily involved in this effort. Approximately 45 percent of the experiments on NIF will be devoted to weapons physics beginning in the FY 2006-FY 2010 timeframe.

ii) **Ignition:** The ICF Program supports a focused scientific program aimed at achieving ignition in the laboratory using NIF by 2010. This represents approximately 45 percent of the experiments planned for NIF. Omega, Z, Trident, and Nike provide supporting research that contributes to this goal. As stated in the NIF mission need statement, the ignition effort also contributes to the fusion energy mission, which is "owned" by the Department of Energy (DOE) Office of Fusion Energy Sciences (OFES).

iii) **High Yield:** The ICF Program supports activities aimed at assessing the feasibility of high yield. This activity occurs primarily on Z. The goal of the high yield effort is to provide the nation a development path for high yield in the 2008-2010 timeframe*, should the nation desire to take this step*. A decision by the US to build a high yield machine may well involve considerations beyond DP. Hence, this high yield strategy is currently in coordination with other offices within the U.S. Government, such as DOE/OFES and the Defense Threat Reduction Agency (DTRA).

iv) **Radiation Effects:** The Hostile Environments and ICF Campaigns support efforts in x-ray source development for nuclear weapons effects testing. The bulk of this work occurs on pulsed power machines (Saturn/Z). Over the past 5-8 years there has been an examination of the use of lasers in this area. Currently, a small fraction (under 10 percent) of the shots planned for NIF are allocated to this activity.

v) **Basic Science:** The ICF and HEDP Grants Programs supports basic HEDP science within and external to the DP labs. A university grants program funds 22 HEDP researchers at universities and other organizations. University researchers presently utilize the Omega laser (National Laser Users Facility), Z, and Trident. As part of a recent reassessment of HEDP Program strategy, the ICF Program has embarked on a study of how to enhance the amount of exciting basic HEDP science executed within the DP labs. This has been found to be necessary to maintain the skill base in the light of delays in NIF. As in many other areas of science relevant to SSP, other agencies have left the task of maintaining the HEDP basic science base to DP. Support of HED science in the broad national interest is a component of the NIF Mission Statement.

vi) **Construction:** In support of the programmatic strategies outlined above, the HEDP Program currently has two construction projects underway: the NIF Project and the Z-backlighter Project

vii) **Supporting Technologies:** ICF and other campaigns also are responsible for the development of technologies required to support other elements of the HEDP strategy. This includes the development and fabrication of advanced diagnostics (including all the diagnostics for Omega, Z, Nike, Trident, and NIF), cryogenics for ignition targets, and laser and pulsed power technology.

DOE HEDP Program Baseline includes the following program elements:

a) HEDP experiments and supporting work (operations, diagnostics, target fabrication) as accounted for in Campaigns 1, 2, 4, 7 & 10 and DSW. Plans for these HEDP activities are balanced within the Stockpile Stewardship Program by the laboratories to meet present and future needs of the stockpile.

b) The NIF Project baseline approved by the Secretary on September 15, 2000. This includes both construction and operating funds through FY 2008.

c) NIF diagnostics and cryogenics required to support weapons physics and ignition goals.

d) In addition to the present ICF facilities and NIF, Atlas and Janus also support HEDP. RTBF costs to cover this suite of facilities are included in the HEDP baseline.

e) Construction of the Z-backlighter.

Appendix C – Stockpile Stewardship Program Business Model

C.1 New Business Model

The approach used by the Office of Defense Programs (DP) to manage the Stockpile Stewardship Program (SSP) involves developing an understanding of both the fixed and variable costs associated with the program. The fixed costs are associated with the physical infrastructure, *i.e.*, the costs associated with maintaining only the infrastructure, facilities, capital equipment, construction, and other functions that are necessary to have a viable nuclear weapons complex. DP has termed fixed costs as Readiness in Technical Base and Facilities (RTBF).

The variable costs are those that are associated with the actual work that is performed within the nuclear weapons complex. DP has established two categories of variable costs. The first category is Directed Stockpile Work (DSW), which are those activities that directly support the day-to-day work and activities associated with the refurbishment and certification of specific weapons in the nuclear stockpile. The second category of variable costs is termed "Campaigns," which are focused science and engineering activities that address critical capabilities, tools, computations and experiments needed to achieve weapons stockpile certification, manufacturing, and refurbishment now and in the future, in the absence of nuclear testing.

The implementation of this approach of identifying both fixed and variable costs of the program provides DP, laboratory and plant managers an improved and coordinated tool for determining the costs associated with managing the nuclear weapons complex. This approach also is key to sustaining the laboratories as premier scientific and engineering institutions, supporting the manufacturing activities necessary to maintain and modernize the stockpile.

Another business practice introduced this year by DP was the establishment of a rigorous planning process that clearly lays out programmatic milestones to be achieved within each element of the SSP. The complete SSP is now defined by a series of program plans that have a five-year planning horizon, each with an accompanying annual implementation plan. The five-year program plans describe the goals and objectives of the program elements, and the annual implementation plans provide detailed sets of milestones that allow for accurate program tracking and oversight.

C.2 Directed Stockpile Work

The DSW Program addresses activities that directly support the readiness of the enduring nuclear weapons stockpile now and for as long into the future as is required.

It focuses on nuclear stockpile life-cycle management, maintains the nuclear deterrent as specified in the Nuclear Weapons Stockpile Plan, the directive signed by the President that establishes the stockpile size and content. It includes stockpile-related workload, policy guidance, coordination, and oversight of all activities that directly support stockpile requirements. DSW policy and program guidance is formulated within DP and implemented by a team consisting of DP, the national laboratories, and the production plants that together comprise the nuclear weapons complex.

DSW encompasses a broad range of activities that focus on the safety, security, and reliability of nuclear weapons. These activities include research, development, and production associated with: weapon maintenance; surveillance; life extension; assessment and certification; baselining; dismantlements; design assessments; engineering; and production readiness across the nuclear weapons complex. DSW represents the programmatic foundation for setting current weapon system activities and implementing future weapon stockpile requirements. The key DSW program goals are to

Maintain the readiness of the deployed stockpile.

- Execute the limited life component exchange program (LLCE),
- Confirm the safety, reliability, and performance of deployed weapon systems, and
- Conduct authorized weapon alterations, modifications and repairs.

Support nuclear deterrent into the future.

- Refurbish the current stockpile to achieve life extension, and
- Provide the capability to modernize weapons.

Dispose of retired weapons and associated components.

- Dismantle retired weapons, and
- Provide for materials and component disposition.

C.3 Campaigns

Campaigns are technically challenging, multi-year, multifunctional efforts conducted across the National Nuclear Security Administration (NNSA) national laboratories, the production plants, and the test site. They are designed to develop and maintain specific critical capabilities that are needed to sustain a viable nuclear deterrent. The goal of the Campaigns is to provide the capabilities needed to address current and future stockpile issues by employing world-class scientists and engineers, and by providing the most advanced scientific and engineering infrastructure. The Campaigns provide a focus and planning framework that enables the laboratories to sustain their scientific preeminence. Campaigns have milestones and specific goals designed to focus efforts in science and computing, applied science and engineering, and production readiness, on well-defined deliverables related to the stockpile. Currently, there are seventeen Campaigns.

Eight Campaigns deal primarily with providing the scientific understanding necessary to certify the nuclear weapons stockpile in the absence of nuclear testing and to support the stockpile modernization required for weapon life extensions.

- *Primary Certification Campaign* – includes experimental activities that will develop and implement the ability to certify rebuilt and aged primaries to within a stated yield level without nuclear testing. Capabilities developed under this Campaign directly support DSW, including the B61, W80, and W76 life extensions, and certification of the newly fabricated W88 pit.

  Goal: Develop the tools required to certify the performance and safety of any newly fabricated replacement or aged primary based on hydrodynamics and generalized materials descriptions.

- *Dynamic Materials Properties Campaign* – includes efforts to develop physics-based, experimentally validated data and models of all stockpile materials at a level of accuracy commensurate with the requirements of primary and secondary certification.

  Goal: Provide complete, accurate and experimentally validated models that describe the state and evolution of material properties in imploding primaries, with special emphasis on plutonium.

- *Advanced Radiography Campaign* – develops technologies for three-dimensional imaging of imploding surrogate-material primaries, with sufficient resolution to resolve uncertainties in primary performance.

  Goal: Provide accurate three-dimensional imagery of imploding surrogate primaries.

- *Secondary Certification and Nuclear-Systems Margins Campaign* – includes experimental and computational activities designed to determine the minimum primary yield needed to produce a militarily effective weapon. The activities in this Campaign will develop a validated, predictive computational capability for each system in the stockpile, determine the primary radiation emission and energy flow, and determine the performance of nominal, aged, and rebuilt secondaries.

Goal: Determine margins and weapon-primary factors necessary to produce a militarily effective weapon.

- *Inertial Confinement Fusion Ignition and High Yield Campaign* – includes experimental activities at the National Ignition Facility (NIF) and other facilities that will enhance experimental capabilities for stewardship. Conditions that can be reached at the NIF, together with the diagnostics available, will also provide enhanced experimental capability for primary and secondary certification and weapons-relevant materials dynamics measurements.

  Goal: Execute high-energy-density physics (HEDP) experiments required for stewardship, including demonstration of ignition.

- *Certification in Hostile Environments (Nuclear Survivability) Campaign* – will validate computational tools for certification, reevaluate nuclear-weapon hostile environments, develop radiation-hardened technologies, and demonstrate certification technologies on the W76 life extension program.

  Goal: Develop certification tools and microsystems technologies required to ensure that refurbished weapons meet stockpile-to-target sequence (STS) hostile environment requirements.

- *Advanced Simulation and Computing (ASC) Campaign* – uses the tools of the Accelerated Strategic Computing Initiative (ASCI) to provide three-dimensional, high-fidelity, full-system simulation software required for engineering, safety, and performance analyses of weapons in the stockpile.

  Goal: three-dimensional, high-fidelity-physics, full-system simulation capability by FY 2004.

- *Weapon System Engineering Certification Campaign* – establishes science-based engineering methods to increase confidence in weapons systems through validated simulation models and high fidelity experimental tests. This Campaign will validate engineering computational models, and will develop a suite of tools to enable science-based certification of the B61, W80, and W76 as required by the Stockpile Life Extension Process (SLEP).

  Goal: Establish a predictive capability integrated with fewer, but smarter, experiments to assess weapon performance with science-based certification.

Three engineering Campaigns focus on providing specific tools, capabilities, and components necessary to support the maintenance, modernization, refurbishment and continued certification of specific weapons systems. These campaigns support both certification and DSW work.

- *Enhanced Surety Campaign* – develops enhanced surety options that may be considered for incorporation in scheduled stockpile refurbishment. This Campaign will develop enhanced surety options for the W80 and W76 weapon systems in time to support their refurbishments.

  Goal: Meet modern nuclear surety standards in time for scheduled weapon refurbishments.

- *Enhanced Surveillance Campaign* – develops the tools needed to predict or detect the precursors of age-related defects before they jeopardize warhead safety or reliability. Material, component, system characterization, and predictive modeling and simulation are central to this activity. With sufficient lead-time, the necessary redesigns, refurbishments, and re-certifications can be made efficiently and cost effectively. The Enhanced Surveillance Campaign develops the technologies and methods, as well as the fundamental understanding of materials properties and weapons science, to improve detection and predictive capabilities. These capabilities will be used to develop new estimates for weapon lifetimes.

  Goal: Provide lifetime assessments and the quantitative decision basis for future life extension programs.

- *Advanced Design and Production Technologies (ADAPT) Campaign* – is designed to accelerate and advance product realization technologies by developing capabilities to deliver qualified refurbishment products cheaper, better, and quicker. This Campaign will develop modeling and simulation tools and information management technologies to enable full-scale engineering development with minimal hardware prototyping, and through totally paperless processes, for monitoring weapon refurbishment activities.

  Goal: Provide the capability to deliver qualified stockpile life extension program refurbishment products upon demand at one-half cost, one-half the current time and with zero stockpile defects by 2005.

Seven readiness Campaigns focus on sustaining the manufacturing base within the nuclear weapons complex. Some manufacturing processes and capabilities are no longer practical. Without a viable manufacturing capability, the U.S. nuclear deterrent cannot be maintained. These campaigns are driven by the current work required to maintain the stockpile as characterized by the SLEP schedule, and the fact that weapons must remain reliable for decades beyond the anticipated deployment period established when they originally were manufactured.

- *Pit Manufacturing and Certification Campaign* – will reconstitute pit manufacturing within the NNSA nuclear weapons complex, including the reestablishment of the technical capability to manufacture and certify all war reserve pits for the enduring stockpile at a capacity of 20 pits per year. These pits will be produced at Los Alamos National Laboratory (LANL).

  Goal: Develop an automated, expandable, robust capability to produce and certify stockpiled and new-design pits, without underground testing, within nineteen months of the establishment of a need for a new pit, and with a stockpile life greater than the weapon system.

- *Secondary Readiness Campaign* – will ensure that future manufacturing capabilities (equipment, people, and processes) are in place and ready for production of secondaries. This includes the reestablishment of special materials processing, replacement of sunset technologies, development of technical work force competencies, and the development of component certification/recertification techniques. This Campaign develops, implements, and maintains the appropriate capability and capacity to accomplish DSW, and responds to surge production scenarios to manufacture/remanufacture replacement components for all weapon systems in the active stockpile.

  Goal: Develop the capability to deliver a first production-unit secondary within 36 months of receiving a request.

- *High Explosives (HE)/Assembly/Disassembly Readiness Campaign* – is focused on ensuring future manufacturing capabilities for high-explosive fabrication and weapon assembly/disassembly.

  Goal: Develop the capability for HE/assembly/disassembly readiness by 2008, by providing the technologies, facilities, and personnel for high-explosives component manufacturing, production re-qualification, and weapon assembly/disassembly/disassembly operations to support an engineering development cycle time of nineteen months.

- *Nonnuclear Readiness Campaign* – focuses on ensuring that future manufacturing capabilities for nonnuclear components will be available.

  Goal: By FY 2006, bring all identified production vulnerabilities to an acceptable level of risk; develop advanced technologies to yield defect-free products at half the traditional cost and within nineteen months after the need is defined.

- *Tritium Readiness Campaign* – will provide a source of tritium commensurate with the Secretary of Energy's Record of Decision announced in December 1998. This designated the Commercial Light Water Reactor (CLWR) as the primary technology option, with a linear accelerator option to be developed as a backup.

Goal: By FY 2006, deliver tritium gas at a steady rate to the Savannah River Site Tritium Loading Facility.

- *Material Readiness Campaign* – includes activities to support the construction of a new highly enriched uranium (HEU) storage facility at Y-12. This will result in the consolidation of long-term HEU material at a state-of-the-art facility. It also will involve planning activities for new nuclear material storage vaults, to provide for long-term storage of national plutonium assets.

  End State: Develop by FY 2005 a fully integrated material management system supporting strategic material needs with either stockpiled material or the capability to produce new material.

C.4 Readiness In Technical Base and Facilities – Maintaining an appropriate infrastructure

Readiness refers to maintaining a state of preparedness to be able to perform necessary activities and functions now and in the future. In addition to ongoing activities, the SSP must maintain the capabilities to design, develop, test, and produce nuclear weapons in the future, if so ordered by the President. The RTBF portion of the SSP serves all of these functions. It contributes in a real and tangible way to confidence in DOE's performance of stockpile stewardship. Readiness is required in three areas. First, it is essential to have high-quality, motivated people with the correct skills to carry out stewardship, resolve unanticipated technical issues, and resume design, development, testing, and production if it becomes necessary. Second, the proper infrastructure must exist to support the activities of these people, both from a stewardship perspective and from the perspective of resuming weapon development, testing and production. This infrastructure must be maintained and upgraded as technology evolves. Third, the special experimental and computational facilities needed for stewardship in the absence of nuclear testing must be developed. RTBF is at the heart of stewardship, and ultimately enables the NNSA to be ready to develop, produce, and test nuclear weapons.

The primary goal of RTBF is to ensure that the infrastructure is in place and available to conduct the scientific, engineering, and manufacturing activities of the SSP. It also encompasses those activities needed to ensure that the infrastructure – utilities, facilities, equipment – are operationally safe, secure and environmentally compliant within a defined level of readiness. The remainder of this subsection summarizes RTBF activities related to facilities and infrastructure, test readiness, simulation infrastructure, and other activities in more detail.

RTBF activities are directed by NNSA federal personnel at Headquarters, supported by the Albuquerque, Nevada, Oakland, and Oak Ridge Operations Offices for contract management, and implemented by contractor personnel at the Lawrence Livermore National Laboratory (LLNL), Livermore, California; LANL, Los Alamos, New Mexico; the Sandia National Laboratories (SNL), Albuquerque, New Mexico, Livermore, California, and Tonopah, Nevada; the Nevada Test Site (NTS), Las Vegas, Nevada; the Pantex Plant, Amarillo, Texas; the Kansas City Plant (KCP), Kansas City, Missouri; the Y-12 Plant, Oak Ridge, Tennessee; and the Savannah River Site, Aiken, South Carolina.

Facilities and infrastructure. At the three DP laboratories and the test site, this includes operation of existing scientific facilities, planning for major new scientific facilities, and planning and construction of smaller facilities necessary to provide a modern, evolving infrastructure. The enormity of developing a comprehensive scientific understanding of all aspects of nuclear weapons has led the laboratories to develop a number of facilities that are unique and of a "national scale." Those presently under construction include the Dual-Axis Radiographic Hydrodynamic Test Facility (DARHT) at LANL, and NIF at LLNL. Considered for construction are the Advanced Hydrodynamics Facility (AHF) at LANL, which would enable high-resolution, multiple-axis proton radiography, and the Microsystems and Engineering Sciences Applications facility (MESA) at SNL, which would provide research, design, and production capabilities for microsystem-based weapon surety options. To prepare for the large computer systems necessary to meet the SSP's simulation objectives, major new computer facilities are under construction at both LLNL and LANL as part of ASCI. Also at the three laboratories and the test site, there is a coordinated, ten-year plan to provide continuous updating of the physical infrastructure by planning, constructing, and eventually operating conventional facilities that are necessary to sustain a constant infusion of new technology into the four institutions.

At the production sites (Pantex Plant, KCP, Y-12, Savannah River Site, and certain facilities at LANL and SNL), facilities infrastructure activities follow a "science-based" approach that aims to provide a weapon production capability that will enable successful, timely execution of planned Life Extension Programs (LEPs). The production facilities, in concert with the weapon design laboratories, must constantly address issues pertaining to facilities, technology, personnel, and business practices. Because of the past cost-saving efforts to downsize the nuclear weapons complex in place rather than build an entirely new, expensive one, significant gaps exist in some areas of capability and capacity that will have to be overcome to meet planned LEPs.

Maintaining test readiness. Activities are conducted at the NTS to preserve the skills and facilities required to resume testing within 24 to 36 months, if so directed by the President. Key and critical positions are identified for the functional areas necessary to safely execute an underground nuclear test. Overall readiness is supported by experimental programs conducted at the test site. In particular, test readiness at NTS is critically dependent on the Campaigns and laboratory-based experiments that exercise high-bandwidth recording and advanced diagnostic development that are not required for subcritical experiments.

Other RTBF activities. The final category of RTBF comprises small but nevertheless important activities required for overall SSP success. Examples include waste management activities, water treatment, and seismic studies. Also included are education and technology partnership activities.

Appendix D – Descriptions of High Energy Density Physics Facilities

D.1 National Ignition Facility – Lawrence Livermore National Laboratory

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is an experimental facility consisting of a laser and target area, and associated assembly and refurbishment areas now under construction. The 192 beam neodymium (Nd) glass laser will be capable of producing an output with an energy of 1.8 megajoules (MJ) and power of 500 terawatts (TW) of laser light at a wavelength of 0.35 micrometers (μm) and with specified symmetry, beam balance and pulse shape. The 192 beams are transported to the target chamber where they irradiate targets for performing experiments studying weapons physics and ignition using deuterium and tritium fuel. The geometry of the beams is arranged for indirect drive fusion although NIF has the capability to be reconfigured in a direct-drive geometry.

The NIF consists of the laser building that houses the laser system, the switch yard that redirects the beams to the target and the target area where the experiments are done. In addition, the Optics Assembly Building where the optics and other components are processed is adjacent to the laser building. The facility has an approximately 20,300 square meters footprint and 38,000 square meters in total area. It is a reinforced concrete and structural steel building that provides the vibration-free, shielded, and clean space for the laser, target area, and integrated control system. The laser building consists of two laser bays, each 31 meters (m) by 135 m long. The target area is a heavily shielded (1.8 m thick concrete) cylinder 32 m in diameter and 32 m high that contains the final laser focusing optics, the target chamber, and the diagnostics. Adjacent to the target area is the diagnostics building for supporting target experiments.

The laser system is designed to generate and deliver high power optical pulses to the target chamber. The system consists of 192 laser beams configured to illuminate the target with a specified symmetry, uniformity, and temporal pulse shape. The laser pulse originates in the pulse generation system. This precisely formatted low energy pulse is amplified and distributed to the 192 beams simultaneously. The pulses are amplified in each of the 192 beams at a 40 centimeters (cm) by 40 cm aperture in groups of eight called a bundle using a multipass architecture. The beams are transported to the target chamber in groups of four where the frequency is tripled to produce 0.35-μm laser light that is focused on the target.

The target area includes a 10-m diameter, low activation aluminum vacuum chamber located in the Target Area of the laser building. The chamber and building structure provide confinement of radioactivity (e.g., x-rays, neutrons, tritium, and activation products). Diagnostics will be arranged around the chamber for a variety of experiments. Structural, utility and other support systems necessary for safe operation and maintenance will also be provided in the Target Area. The target chamber, the target diagnostics, and staging areas will be capable of conducting experiments with cryogenic targets required for ignition. The baseline is for indirectly driven targets. An option for future modifications to permit directly driven targets is included in the design.

Thousands of optical components will be required for the 192-beam NIF. These components include laser glass, lenses, mirrors, polarizers, deuterated potassium dihydrogen phosphate crystals, potassium dihydrogen phosphate crystals, pulse generation optics, debris shields and windows, and the required optics coatings. Optics includes quality control equipment to receive, inspect, characterize, and refurbish the optical elements.

Construction of the conventional facilities is essentially complete. First cluster testing is projected to occur in late FY 2006, with project completion (192 beams) in late FY 2008.

For reference, an explanation of the NIF beam geometry is included in Appendix E.

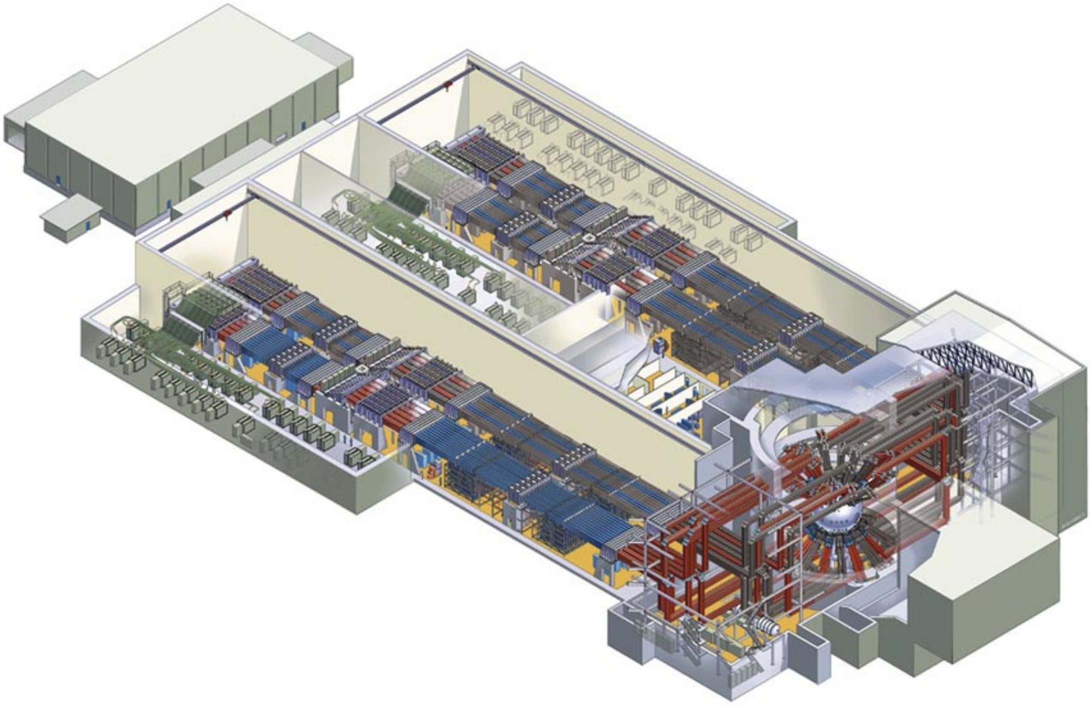

Figure D-1. The National Ignition Facility.

D.2 Z Pulsed-Power Accelerator – Sandia National Laboratories

The Z pulsed-power accelerator provides critical experimental data to the Stockpile Stewardship Program (SSP) by converting stored electrical energy into sub-microsecond, high-power electrical pulses. In particular, Z provides data for five SSP campaigns: Dynamic Materials Properties, Secondary Certification, Nuclear Survivability, Inertial Confinement Fusion (ICF) and High Yield, and Advanced Simulation and Computing (ASC). Z operates in either a z-pinch mode by vaporizing and imploding an array of 200-400 wires that are each a few microns in diameter to provide x rays, or in a short-circuit mode to provide intense magnetic fields. In the z-pinch mode, Z routinely produces more than fifty times the x-ray energy and a factor of five more x-ray power than any currently operating laser. In the short-circuit mode, isentropic compression experiments and magnetically accelerated flyer plate experiments are producing accurate high-pressure equation-of-state data.

Z's predecessor, Particle Beam Fusion Accelerator (PBFA) II, was constructed for the ICF Program in 1985 to produce high voltages (10-30 mega volts [MV]) to focus light ions on pea-sized capsules, producing fusion. In 1996, PBFA II was modified to a high-current, low-voltage (20 mega ampere [MA], 2.5 MV) configuration by replacing the inner 4.5 m of the accelerator. The z-pinch experiments with the modified facility were so successful that, by mid 1997, the facility was renamed Z, and light ion research was discontinued a year later. Today, Z and the Omega laser at the University of Rochester are the major operational, HEDP facilities at the National Nuclear Security Administration (NNSA) national laboratories.

During the last four years, the operations crew on Z has made incremental improvements in daily processes, developed innovative methods to reduce experimental preparation time, and added an extensive suite of time- and space-resolved diagnostics. In FY 2000, a new control monitor system was implemented that adopts modern industrial control technology.

In the third quarter of FY 2001 the Z-Beamlet backlighter will begin to be used as a diagnostic on Z experiments for the DMP, SC, NS, and ICF Campaigns. The kilojoule-class laser, originally named Beamlet, was transferred to Sandia from LLNL in the fall of 1998. Beamlet was constructed in 1994 by LLNL as a one-beamline prototype of the NIF-laser system.

The accelerator hardware outside the vacuum insulator stack section is a remnant of the 16-year-old PBFA II technology and is not optimized electrically for today's configuration. Moreover, the demand for experimental shots on Z now exceeds 500 per year – much greater than the 154 shots during FY 2000 – and weapon scientists who use Z have expressed interest in improving the quality and precision of the data and in increasing the x-ray energy produced. Refurbishing Z would extend the lifetime of its components and improve its performance, reliability, and shot rate. The refurbishment would also produce higher-quality data at higher x-ray energies and at higher pressures. The table below shows the present performance of Z and the enhanced performance expected with a refurbished Z operating at an increased current of 26 MA.

Experimental Capability of Z and the Proposed Refurbished Z Machine

Capability	Z today	Z after refurbishment
radiated power in x rays	230 TW	350 TW
radiated energy in x rays	1.8 MJ	3.0 MJ
T_{rad} for weapon physics VH/DH*	150/220 eV	170/250 eV
T_{rad} for ICF VH/DH*	75/180 eV	85/205 eV
peak pressure with ICE technique	2.5 Mbar	10 Mbar**
velocity of magnetic flyer plate	21 km/s	43 km/s**
energy radiated above 1 keV/5 keV/8 keV	400/125/10 kJ	700/350/30 kJ

*VH is a vacuum hohlraum; DH is a dynamic (imploding) hohlraum.

**Estimates for ICE pressures and flyer plate velocities are based on a one-sided design.

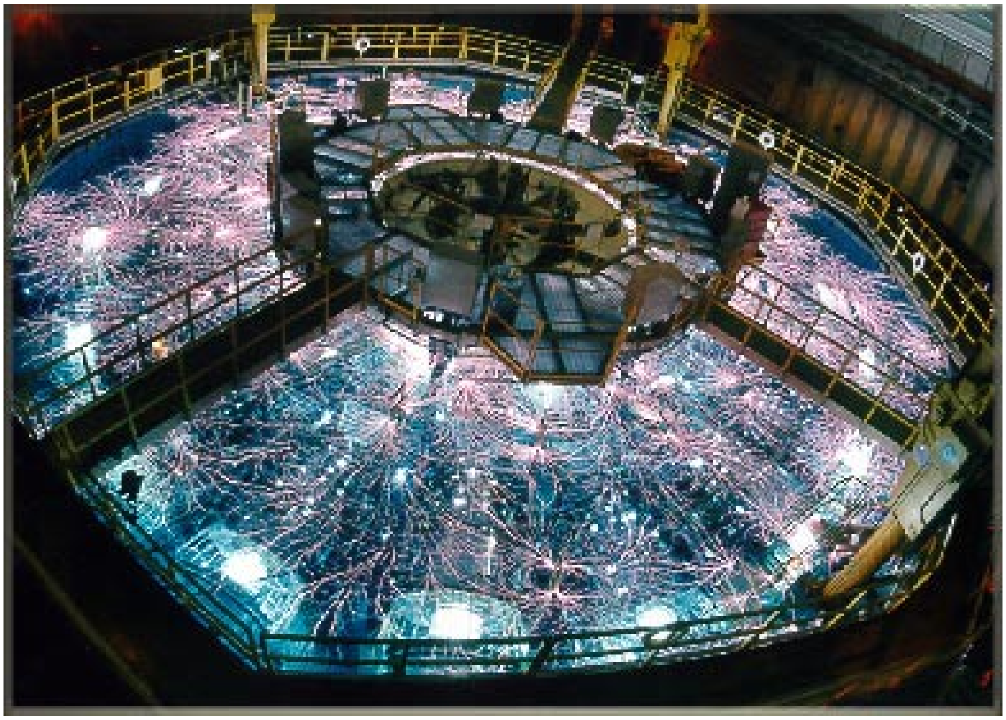

Figure D-2. Z accelerator.

D.3 Omega Laser Facility – University of Rochester

The Omega Laser Facility is used to conduct ignition and other HEDP experiments in support of the nation's SSP, and operates the National Laser Users' Facility program. Omega is located at the University of Rochester's Laboratory for Laser Energetics (UR/LLE) and is operated under a cooperative agreement between the Department of Energy (DOE) and the University of Rochester. UR/LLE is the lead laboratory for studying direct-drive inertial confinement fusion. The upgrade of the Omega laser to its present capability was recommended by a 1990 National Academy of Science review of NNSA's ICF program. Omega was completed (on budget and on schedule) at a total estimated cost of $61million in May 1995 after a four and one-half year construction project. The facility is housed adjacent to the UR/LLE's research complex in a 66-m by 27-m optically stable, clean room building, separated into a laser bay and a target bay. The laser is a master oscillator/power amplifier configuration.

Omega's design parameters, which have been met or exceeded, are given below:

Energy on target	Up to 30 kJ
Wavelength	351 nm
Lasing medium	Nd-doped phosphate glass
Number of beams	60
Irradiation uniformity	1 percent - 2 percent
Beam-to-beam energy balance	3 percent - 4 percent
Pulse shaping	400:1 contrast
Repetition rate	1 shot per hour

Target irradiation is at the third harmonic of the fundamental 1054-nm-wavelength laser radiation (351 nm). Ultra smooth, uniform beams are produced by using two-dimensional smoothing by spectral dispersion (two-dimensional smoothing by sprectral dispersion [SSD]) at 1-THz bandwidth, distributed phase plates, and distributed polarization phase rotators. The frequency conversion and smoothing by spectral dispersion technologies were invented by LLE and are now used on all large laser facilities. A variety of pulse widths (from 100 ps to 4 ns) and pulse shapes are possible. A cryogenic target handling system allows the filling and shooting of spherical targets that are layered and characterized. Omega is the first, and currently the only, facility that has the ability to produce and shoot high quality, layered, spherical cryogenic targets. The 3.3-m diameter, vacuum target chamber has 60 lens ports and 32 diagnostic ports. Six diagnostic insertion mechanisms are installed to handle portable diagnostics. A full suite of fixed and portable diagnostics are available, including charged particle and calorimetric, x-ray imaging, x-ray spectroscopy, x-ray framing cameras, time-resolved x-ray imaging, and nuclear and particle diagnostics._

While it was designed as a direct-drive facility, Omega has demonstrated its flexibility by operating in a variety of configurations. These include symmetric irradiation of spherical targets with 60 beams, planar one- or two-sided irradiation with subsets of the 60 beams, and indirect-drive irradiation of cylindrical hohlraums with up to 40 beams or tetrahedral hohlraums with 60 beams. Omega's versatility and productivity are demonstrated by the completion of 1153 experimental target experiments in FY 2000.

The Omega Facility has provided LLE with an expertise in manufacturing high-damage-threshold large optics. All the large optics used in Omega were manufactured and assembled in-house. This includes ion-etched phase plates and sol-gel or hard oxide coatings of all optics. LLE has developed high-damage-threshold polarizers for the NIF. The damage thresholds achieved exceeded specifications and were significantly higher than any other commercial vendor was able to produce. As a result, LLE is now manufacturing more than over 50 percent of NIF's polarizers and large mirrors and all of NIF's deformable mirrors.

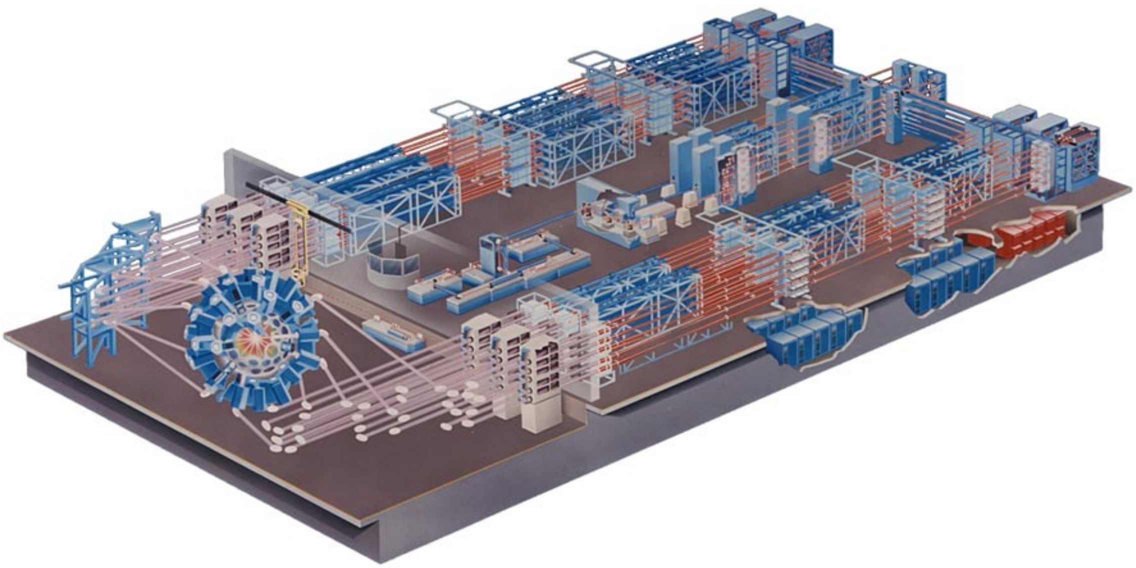

Figure D.3. The Omega laser.

D.4 Saturn Accelerator – Sandia National Laboratories

The two major z-pinch drivers at SNL are the Saturn and Z accelerators. Saturn can drive a 10 MA peak current pulse into a z-pinch with a ~70 ns rise time. By varying the material in the z-pinch load, a variety of x-ray sources can be produced. The principal sources and yields for Saturn are

Al70 kJK-shell line radiation at 1.7 keV plus continuum radiation above 2.2 keV
Ar35 kJK-shell line radiation at 3.2 keV

As with all thermal radiators (z-pinch or laser produced), a substantial flux of photons at energies lower than the K shell or L shell is produced and needs to be filtered out for most weapons effects experiments. The filters vaporize and become sources for material debris onto experiment samples, along with other vaporized material from the z-pinch source region. Some experiments are normally sufficiently fast enough to keep the debris impact from perturbing the experiment, other experiments, such as impulse measurements, require debris mitigation techniques to allow measurements to be made over a longer period of time. Mitigation techniques have been developed and are used, as needed, at Saturn.

The Saturn facility was initially designed as a bremsstrahlung source. Saturn sources are unique in providing a high-fidelity, hot x-ray test bed, critical for certifying stockpile electronic subsystems. The Saturn design includes flexibility in directing power flow in the load region, so that both bremsstrahlung and z-pinch sources could be developed and utilized.

Figure D-4. The Saturn facility.

D.5 Nike Laser Facility – Naval Research Laboratory

The 56-beam krypton fluoride (KrF) Nike gas laser produces 4,000-5,000 J of UV light in a 4-ns pulse. Nike's unique feature is its excellent beam uniformity, about a factor of ten better than the best existing short-wavelength glass lasers. By using a KrF laser with induced spatial incoherence (ISI) optical smoothing, the modulations in the laser focal profile are only one percent in one beam and <0.3 percent with a 44-beam overlap. Nike is used in laser-target experiments, to determine if this laser uniformity is necessary and sufficient to accelerate a direct-drive target under fusion-like conditions, without excessive hydrodynamic distortion or fuel preheat.

Early research with Nike emphasizes the science of laser fusion. The laser also has several other possible applications:

- Uniform and cold compression of materials to 3-5 Mbar;
- Efficient generation of multi-keV x-rays with low debris, to simulate nuclear weapons effects; and
- Interaction of 10-20 Mbar uniform shocks, with non-uniform material structures, to aid evaluation of the aging nuclear weapons stockpile.

The propagation bay for the laser system is a 155-ft long insulated room. The temperature throughout can be held uniform, to within a half degree Fahrenheit, so that a diffraction-limited beam can propagate back and forth, without distortion. Charcoal filters eliminate ultraviolet (UV) absorbing gases. At each mirror array, all 56 beams can be simultaneously aligned, in a few seconds, by an automatic alignment system. The 60 cm by 60 cm KrF amplifier cell is pumped from two sides by identical electron beams generated from Marx banks. The large magnetic field coils of 2-4 kG are used to guide the electron beams through the gas cell. The Nike laser system uses both discharge preamplifiers and E-beam pumped amplifiers. Because the E-beam amplifiers have a long-pulse duration, the laser beams are "multiplexed" into 56 separate beams that pass through the amplifier successively and are then recombined onto the target. Forty-four of the beams are used for target acceleration and twelve are used to produce a backlighter for target diagnostics.

Nike uses planar foil targets. This geometry is better suited for evaluating the imprint by laser non-uniformities and for diagnosing growth of the more damaging Rayleigh-Taylor instability modes. The experiments use target thicknesses, target materials, laser pulse durations, and laser pulse shaping that match the parameters of a high-gain direct-drive fusion target as closely as possible. High-mode capsule perturbations can be evaluated using flat foils. Lower-mode, spherical perturbations are better studied, with glass-laser implosion facilities.

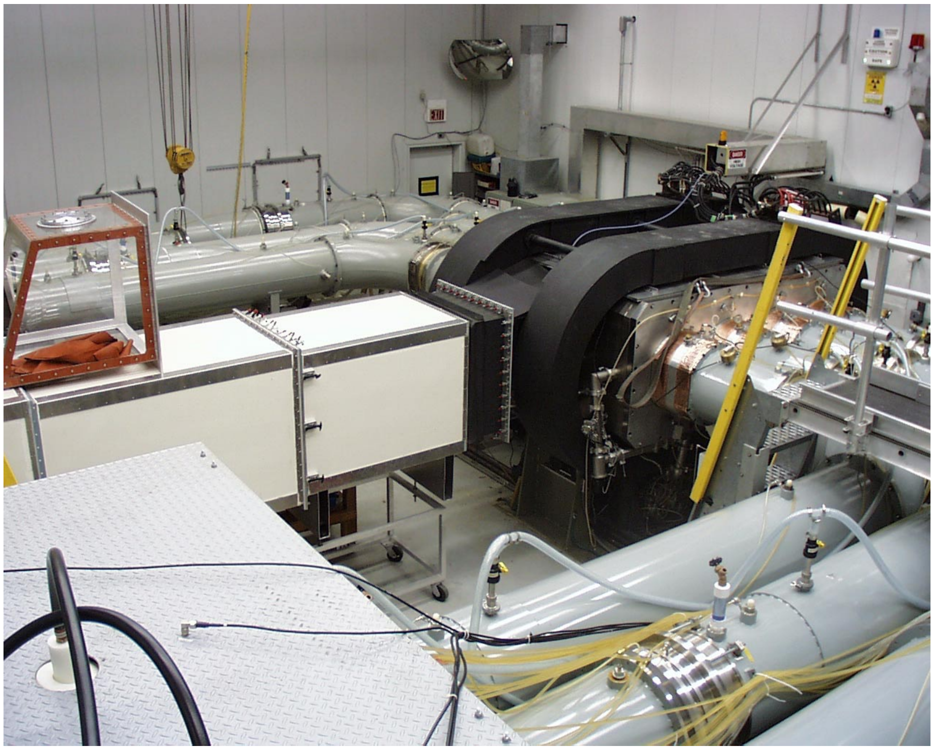

Figure D-5. The Nike KrF laser facility.

D.6 Trident – Los Alamos National Laboratory

Trident, at LANL, provides a capability to conduct experiments requiring high-energy laser-light pulses. Trident is operated as a user facility that principally supports the NNSA DP ICF and HEDP Programs, as well as basic research. Trident is a neodymium-glass-laser, capable of delivering an energy of up to 400 joules, at a wavelength of 1.054 nm, in a 1-ns pulse in each of two 20-cm beams, and up to 40 joules in one 10-cm beam. The two 20-cm beams are frequency converted to the second harmonic (527 nm) before being focused onto the target. The smaller beam can either be operated in the fundamental, or in the 2nd or 3rd harmonic.

In May 1998, a second target bay and target chamber was added to the Trident Facility, as part of the High Energy Density Experimental Laboratory addition. The target chamber, focusing lenses, transport optics, frequency conversion crystals, and experimental diagnostics were acquired from the UR/LLE, where they were used on the original Omega laser system. A ten-inch manipulator (TIM), which is the ICF standard for positioning diagnostics, has been installed on this chamber. Soon the facility will be available for check out and testing of TIM-based diagnostics.

The major change to Trident during the past year that greatly contributed to its ability to carry out cutting-edge experimental work was the modification of the “C” beamline (“backlighter beam”) to a near diffraction-limited beam, with modest energy. This has allowed a number of experiments to be performed that require the interaction of a single laser speckle with a pre-formed plasma. With regards to enhancing Trident, the major activity has been the construction of the TIM, which eventually will be attached to the new target chamber, allowing the interchange of diagnostics between Omega and Trident.

Figure D-6. The Trident facility

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D.7 Atlas – Los Alamos National Laboratory

Atlas is a pulsed-power facility at LANL, developed to drive high-energy-density experiments to study hydrodynamics and material properties under extreme conditions. The system is designed to implode heavy-liner loads in a z-pinch configuration. The Atlas capacitor bank consists of an array of nineteen 240-kV Marx modules storing a total energy of 23 MJ. The bank is resistively damped to limit fault currents and capacitor voltage reversal, and has ~16 nH initial inductance. The current is propagated radially from the Marx generators, to a one-meter radius power ring, by 24 vertical, tri-plate, oil-insulated transmission lines. A combination of flat and conical, radially converging transmission lines deliver the current to load from the one-meter radius. The peak current of 30 MA is delivered in four microseconds. The load is housed in a 1.8-m diameter, stainless steel vacuum chamber, which provides for debris containment and good diagnostic access. For many applications, the Atlas liner will be a nominal 47-gram aluminum cylinder of 4-cm radius and 4-cm length. Liner driving velocities of ~14 km/s are obtainable, without melting of interior surfaces. An inner cylinder of heavier target material, with diagnostics, is placed within the driver liner. Using composite layers and a variety of liner and interior target designs, a wide variety of experiments in ~cc volumes may be performed. These include:

- Shock compression experiments up to ~2 TPa (~20 Mbar);
- Quasi-adiabatic compressions up to six-fold compression and above 10 TPa;
- Nonlinear and turbulent hydrodynamic instability studies over multi-centimeter distances;
- Experiments with dense, strongly coupled plasmas;
- Studies of material responses at very high strains and strain rates;
- Material studies in ultrahigh magnetic fields; and
- Magnetized target fusion experiments.

Strongly coupled plasma experiments are possible by imploding a liner onto a target assembly consisting of a low-density, preheated plasma, confined between high-density cylinders. Using a relatively small auxiliary capacitor bank to explode a wire array produces the preheated plasma.

The Atlas construction project began in 1995, with engineering design and component testing. Construction and acceptance testing were recently completed, slightly under the $48 million budget and one month ahead of schedule. The project passed its most demanding technical milestone on December 15, 2000, when it met full electrical specifications, by producing a current of 28.7 MA.

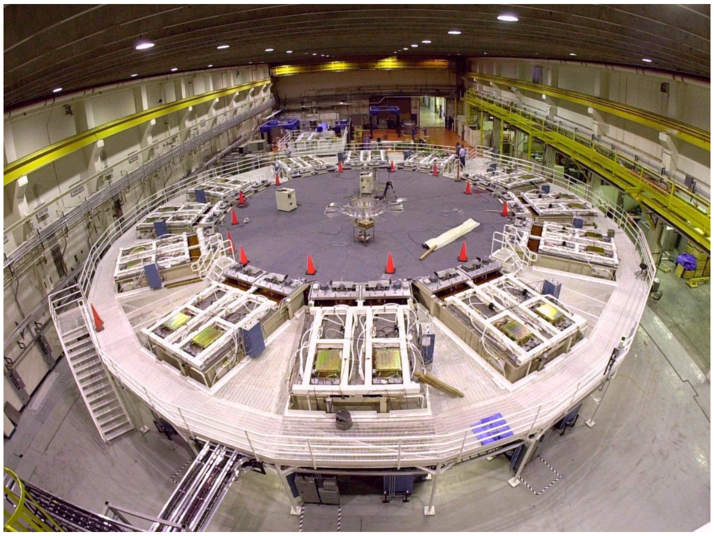

Figure D-7. The Atlas facility.

D.8 Janus – Lawrence Livermore National Laboratory

The Janus laser is presently being operated to perform short-pulse laser interaction studies for investigating dense matter physics relevant to SSP and basic material studies. Originally, the two-beam laser was completed in 1975 to demonstrate laser compression and thermonuclear burn of deuterium-tritium. During the intervening years, Janus was used to study a variety of laser-target interaction physics issues, including laser-plasma interactions. In the 1990's, a short-pulse capability was developed for Janus.

The present configuration of the system is called JanUSP. JanUSP is a significant upgrade to LLNL's longstanding ultrashort-pulse laser capability. Research on ultrashort-pulse lasers, with pulse lengths lasting from a ns to a ps) has been the focus of intense activity at LLNL since the mid-1980s. The work arrived at a major milestone in the late 1990s when LLNL's Petawatt laser achieved record-breaking levels of power, more than 10^{15} watts, and irradiance approaching a 10^{21} W-cm^{-2}, at an energy of approximately 680 joules, before it was shut down. At 200 terawatts and 15 joules, JanUSP has a fraction of the power and energy, respectively, of the Petawatt. However, with its shorter pulse length (85 femtoseconds) and smaller spot size (2 micrometers), it can access different HEDP regimes.

Figure D-8. The Janus laser.

The machine's front end is a commercial oscillator that produces 75- to 80-fs pulses of 800-nm light. The low-energy laser pulses are passed through diffraction gratings, made by Livermore's Diffractive Optics Group. The gratings drastically stretch pulses out in time, so that they do not distort and eventually damage the laser optics. The stretched pulses are energized by a series of amplifiers, using increasingly larger titanium-doped sapphire crystals. The final amplification stage features a 10-cm diameter, 5-cm thick, titanium-doped sapphire crystal, the largest in the world, and one that required three years to be produced commercially. Energizing this crystal is 130-J green light from the Janus laser. The fully amplified light is recompressed to its original pulse length and focused onto a target inside a 2-m diameter chamber.

	Janus 1996	JanUSP
Total Energy	6-10 Joules	15 Joules
Pulse Length	600 fs	75-80 fs
Peak Intensity	5 x 10^{18} W/cm^2	10^{21} W/cm^2
Wavelength	800 nm, 400 nm	800 nm

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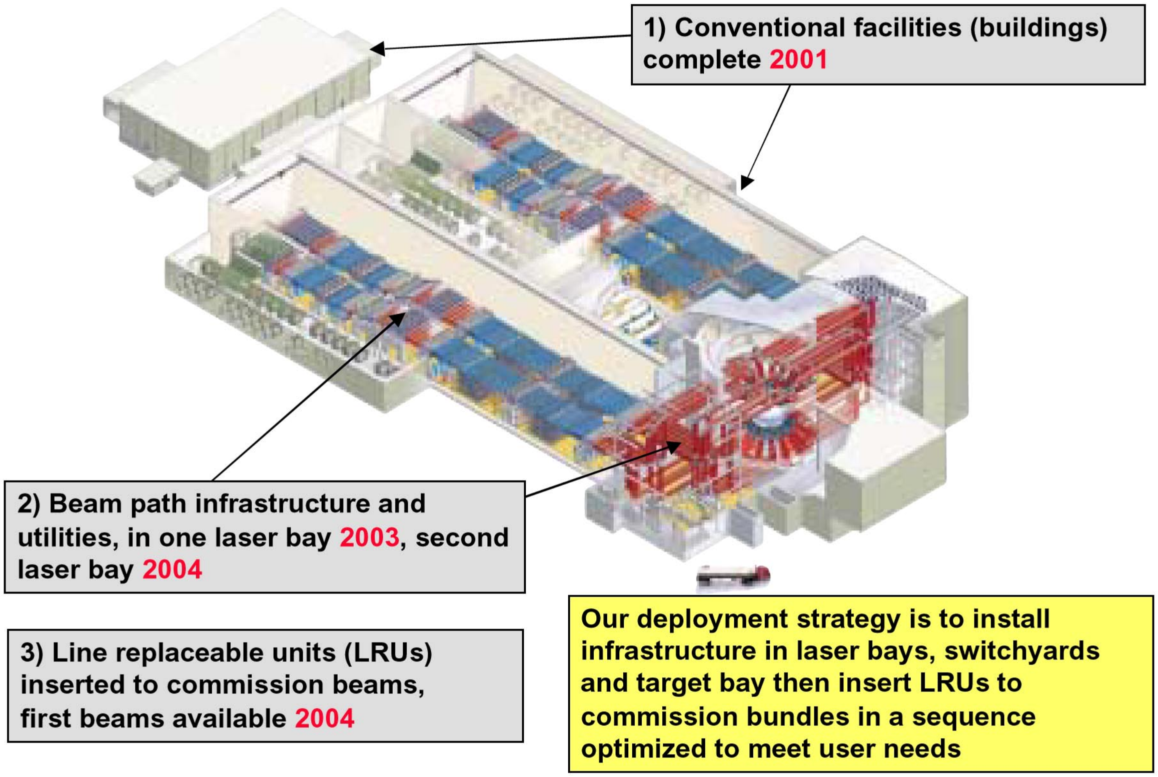
Appendix E – Deployment Strategy for the National Ignition Facility

The deployment strategy for the National Ignition Facility (NIF) has been developed during the past several years, in consultation with the user community. The result is a beam-installation plan for NIF that can be optimized to better meet users' needs throughout the deployment period when NIF will be used to support many user missions. This plan for commissioning NIF beams has become known as the "Mission First" deployment strategy, a strategy that incorporates flexibility in the sequence in which beams are commissioned and become available for experiments. This flexibility allows facility capabilities such as symmetric beam geometry to be available when determined by mission priorities.



1) Conventional facilities (buildings) complete 2001

2) Beam path infrastructure and utilities, in one laser bay 2003, second laser bay 2004

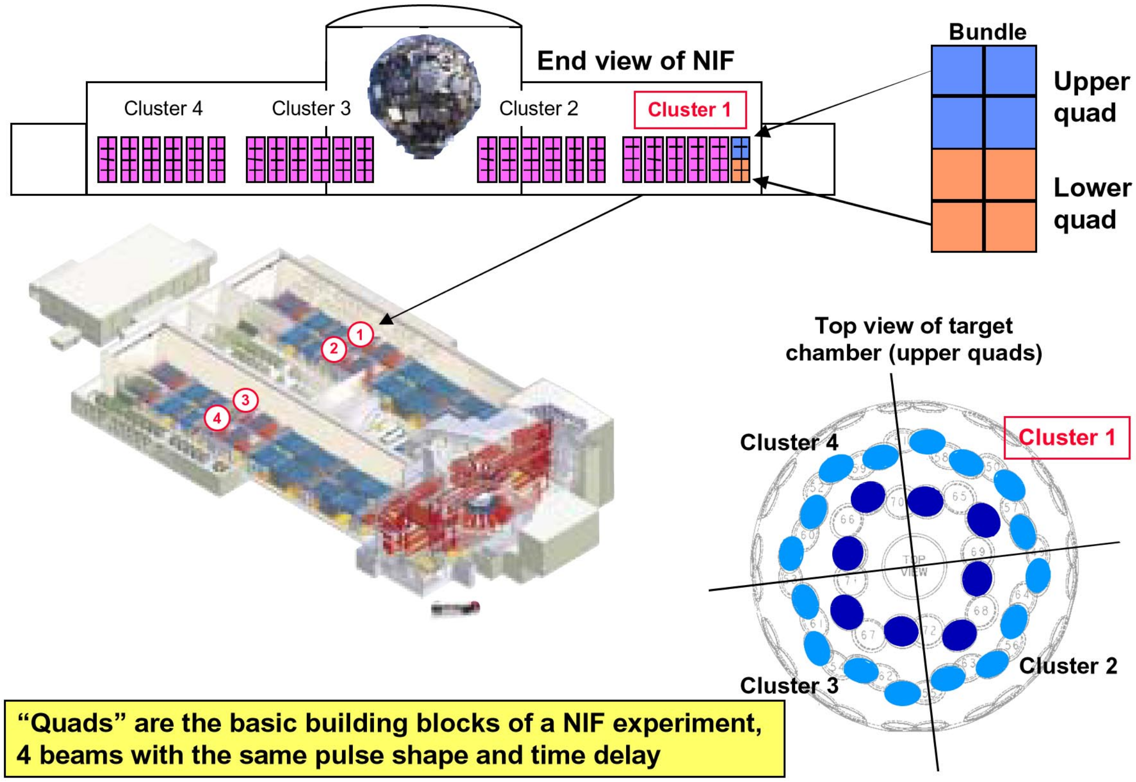
3) Line replaceable units (LRUs) inserted to commission beams, first beams available 2004

Our deployment strategy is to install infrastructure in laser bays, switchyards and target bay then insert LRUs to commission bundles in a sequence optimized to meet user needs

Figure E-1. NIF consists of 3 major parts, the conventional facilities (buildings and climate control systems), the supporting beam path infrastructure (beam tubes, amplifier and vacuum vessels), and the laser hardware inserted into the system, referred to as "Line Replaceable" units (LRUs).

The laser hardware for NIF is located in two laser bays, as illustrated in Figure E-1. Each laser bay provides beams to the left or right hemisphere of the target chamber. Figure E-2 shows how each laser bay contains two "clusters" of 48 beams each. Clusters have common mechanical infrastructure and share some parts of the utilities and controls systems. Within each cluster there are six "bundles" of eight beams each.

The eight beams in a bundle share common power-conditioning systems and amplifier environment. Many of the LRUs, such as pockels cells and transport mirrors, are shared by the beams within a bundle. A bundle is the smallest unit of NIF that can be fired independently without perturbing neighboring beams. It is also the smallest unit that makes sense to commission by installing and activating LRUs. Consequently, the deployment strategy comprises sequential installation of bundles. Each bundle contains two groups of four beams that are known as "quads." Half of the quads are mapped onto the upper hemisphere of the chamber and half to the lower hemisphere. Beams within a quad share the same pulse shape and beam delay and the four beams are located together at the target chamber. The quad is the natural building block when planning complex experiments at NIF.



"Quads" are the basic building blocks of a NIF experiment, 4 beams with the same pulse shape and time delay

Figure E-2. The 192 beams of NIF are arranged in quads (four beams), bundles (eight beams), clusters (48 beams) and laser bays (96 beams). The quad of four beams is the natural planning element for NIF experiments as the four beams in a quad are co-located on the chamber and share the same pulse shape and delay.

Figure E-3 shows that symmetric configurations of quads require beams from all clusters. The figure also illustrates the color-coded subsets of symmetric quads that are the building blocks of the Mission First deployment.

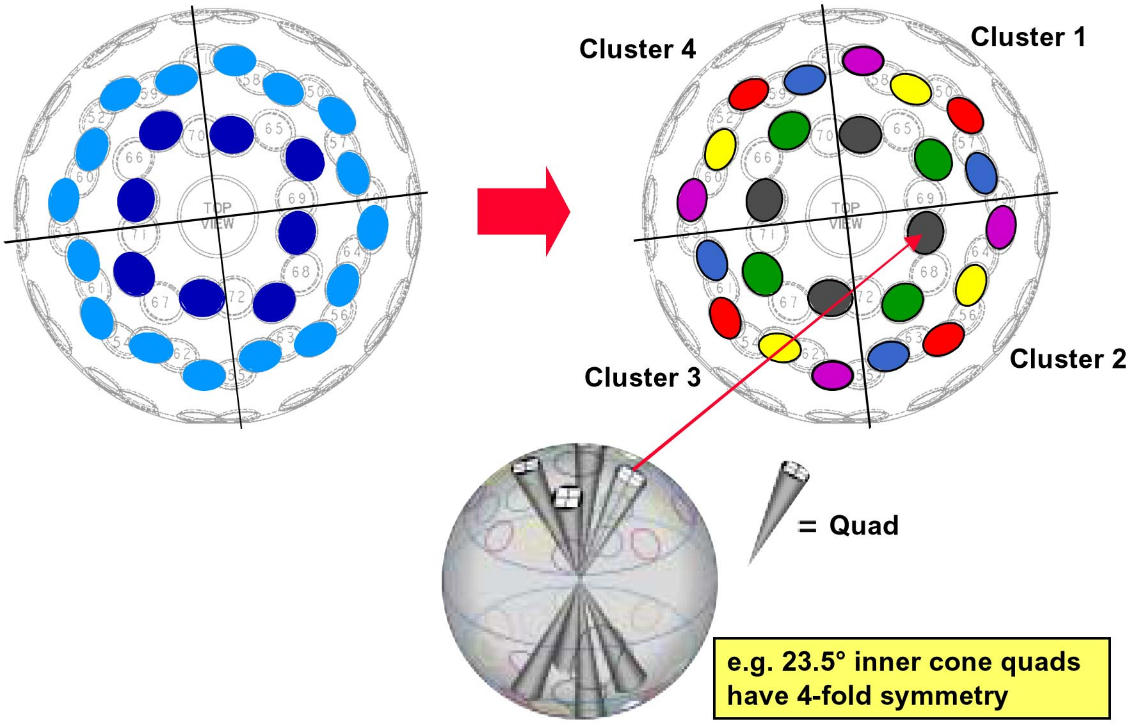


Figure E-3. Top view of the NIF chamber showing how groups of quads have been identified that have four-fold rotational symmetry about the vertical axis and are color coded accordingly.

By completing the infrastructure in each laser bay prior to beam commissioning, the deployment strategy allows the sequence of beam installations to be optimized to meet users' needs. The infrastructure can be considered as a chandelier into which the light bulbs, the LRUs, can be installed in any sequence desired by the operator.

Experiments during the deployment phase of NIF can be divided into three broad categories, as summarized in Figure E-4.

1) Experiments that require symmetric illumination of a hohlraum, oriented such that beams enter through upper and lower laser entrance holes (LEHs) and have a rotational symmetry about the vertical axis. Typical experiments use the symmetric x-ray field in the hohlraum to implode spherical capsules (see Figure E-4a).

2) Experiments that require less symmetry but a large amount of energy in beams incident through one LEH of a half hohlraum or "halfraum." Typical experiments use the x-radiation in the halfraum to drive shocks and other phenomena in a package at the end of the halfraum (Figure E-4b). These experiments can be performed with the halfraum axis either horizontal or vertical.

3) Experiments that use the beams to directly illuminate targets and generate pressure from material ablation to drive shocks and accelerate thin foils (see

Fig 4c). These experiments benefit from beams that are grouped within a small solid angle close to the foil normal.

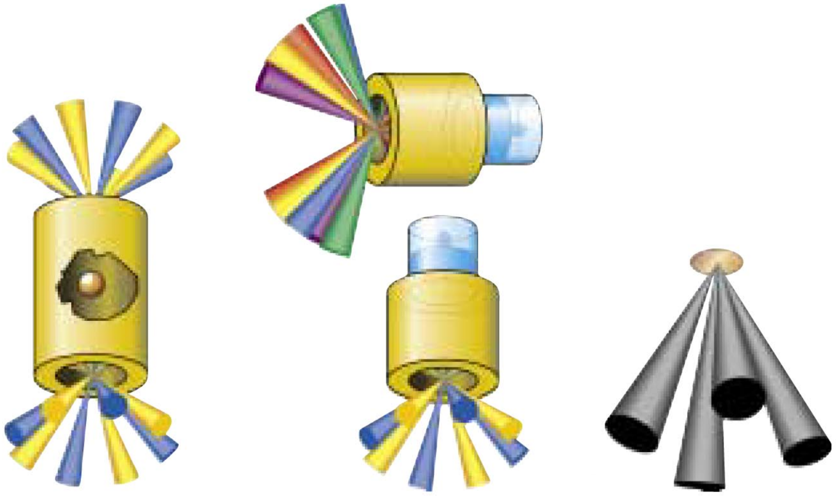

a) b) c)

Figure E-4. Three of the target geometries to be employed by NIF users, a) vertical hohlraum with azimuthally symmetric beams from the top and bottom of the target chamber, b) halfraum with a single cluster of beams incident on the LEH from the top and bottom of the target chamber or with symmetric beams incident from the bottom of the target chamber, c) planar foil directly illuminated by beams from the bottom of the target chamber. Each colored quad in the figure represents four beams.

For each of these experimental geometries, other quads will be used to illuminate separate x-ray emitting plasmas (backlighters) that are used to radiograph the main experiment. The diagrams show colored "quads" incident on various targets. Each colored quad represents four beams. Quads of the same color have four-fold rotational symmetry about the vertical axis.

The deployment strategy, with early installation of infrastructure, allows flexibility in choosing a deployment sequence that will satisfy the maximum number of users at any point in time. It retains that flexibility throughout the deployment, so that, as mission priorities change, so can the facility capabilities.

Figure E-5 summarizes the current deployment sequence and schedule for NIF. The details of the bundle sequence are in the process of being optimized. NIF Mission Support has a milestone to work with user groups to develop a consensus for the initial deployment sequence by April 2001.

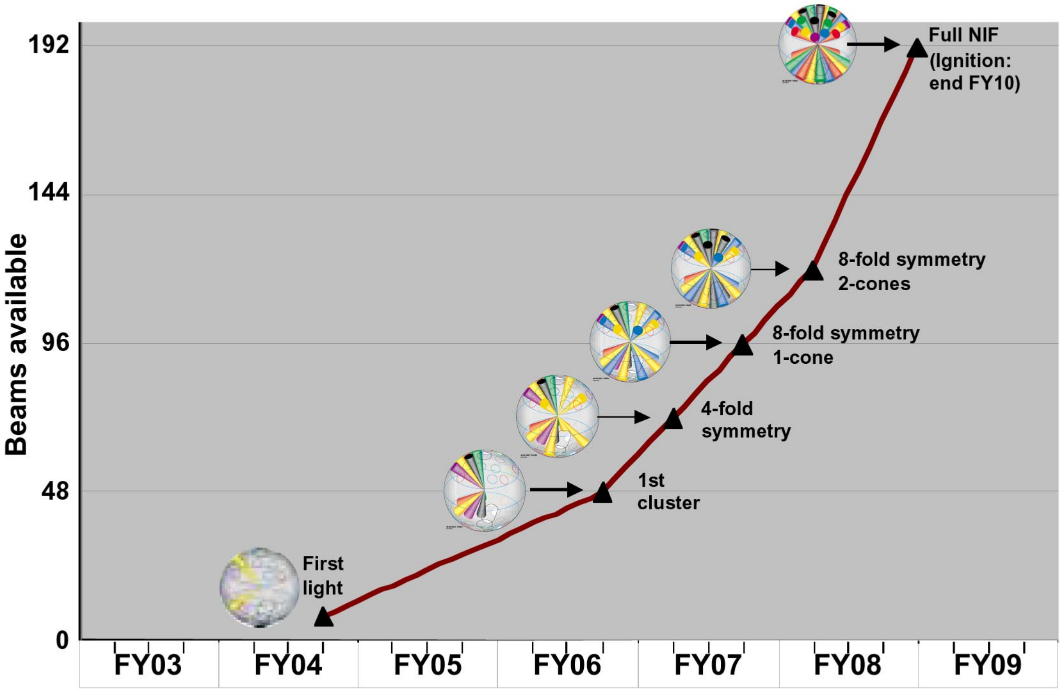


Figure E-5. Mission first deployment sequence and the baseline NIF deployment schedule. Quads of four beams are shown as colored cones within the NIF target chamber.

The deployment sequence, as shown in Figure E-5, begins with the commissioning of a single bundle (first light) that can be used in early direct-drive equation-of-state and hydrodynamics experiments (Figure E-4c), as well as diagnostic technique development. The utility of the facility for high-energy-density experiments increases significantly next when a cluster of 48 beams is available (1^{st} cluster). This configuration will allow weapons physics experiments with horizontal halfraums with up to 200 kJ of energy in the halfraum in ten quads and up to 40 kJ available in backlighter beams.

With completion of full infrastructure in both laser bays beams can be added in groups with four-fold rotational symmetry about the vertical axis. The sequence, as shown in Figure E-5, adds eight quads of beams, which are all oriented 44.5° relative to the vertical axis (shown in yellow). This configuration allows experiments that require symmetry to begin in vertical hohlraums with up to 160 kJ of energy in the 32 symmetric beams, with the remaining beams from the first cluster available as backlighters. Early ignition experiments can begin to develop symmetry measurement techniques, as well as weapons physics experiments that require symmetry, such as convergent-mix experiments and high-temperature hohlraum development.

The next step is to add a further set of four-fold symmetric, 44.5° beams (shown in blue) providing an eight-fold rotational symmetry with up to 320 kJ available for vertical hohlraum experiments with 64 symmetric beams, and the other 32 beams available for backlighting. The increasing symmetric energy will allow all experiments requiring symmetry to move to more interesting HED regimes.

With the addition of eight quads of 23.5° beams (shown in gray in Figure E-5) the total number of beams available is 120, 96 of which are arranged in two cones (at 23.5° and 44.5°) relative to the hohlraum axis. These 96 beams are essentially half of the fully symmetric NIF and have a similar distribution of energy between inner (23.5°) and outer (44.5°) cones. With this configuration, independent pulse shaping on the inner and outer beams allows greater control of the symmetry of the x-ray field experienced by an imploding capsule, allowing higher convergence implosions that are more relevant to future ignition experiments. Experiments to tune time-dependent symmetry and time multiple shocks in imploding ignition capsules can make significant progress at this point. With the introduction of the 23.5° beams, direct-drive experiments, such as shown in Figure E-4c become more useful, with the narrow cone angle of the 23.5° beams allowing the foil target to accelerate further before the finite focal spot size makes the experiment two dimensional. At this point there are twelve symmetric quads at the top and bottom of the chamber, allowing experiments to be performed with up to 240 kJ incident through one LEH of a vertical halfraum (Figure E-4b).

After 120 beams, the remaining beams are added in symmetric sets, allowing increasing energy or backlighter flexibility in many experiments, until the full 192 beams are available with 16-fold rotational symmetry.

Figure E-6 shows the operations plan for NIF during the deployment and thereafter. There will be a greater volume of installation and commissioning work during the period prior to completion of 192 beams, which will limit shot operations to one shift per day. During that period, there will be a total of 250 shots per year available for user experiments. After commissioning all 192 beams, there will be more operations shifts available and the shot rate will ramp up to greater than 700 shots per year. The governance process for NIF, which will resolve issues, such as the balance between the different user groups and oversubscription of NIF in the FY 2006 to FY 2008 timeframe, is presently being set up by the NIF Director with the participation of the National Nuclear Security Administration national laboratories. Figure E-6 illustrates that NIF will be actively producing data, in support of stockpile stewardship, well before the facility is completed.

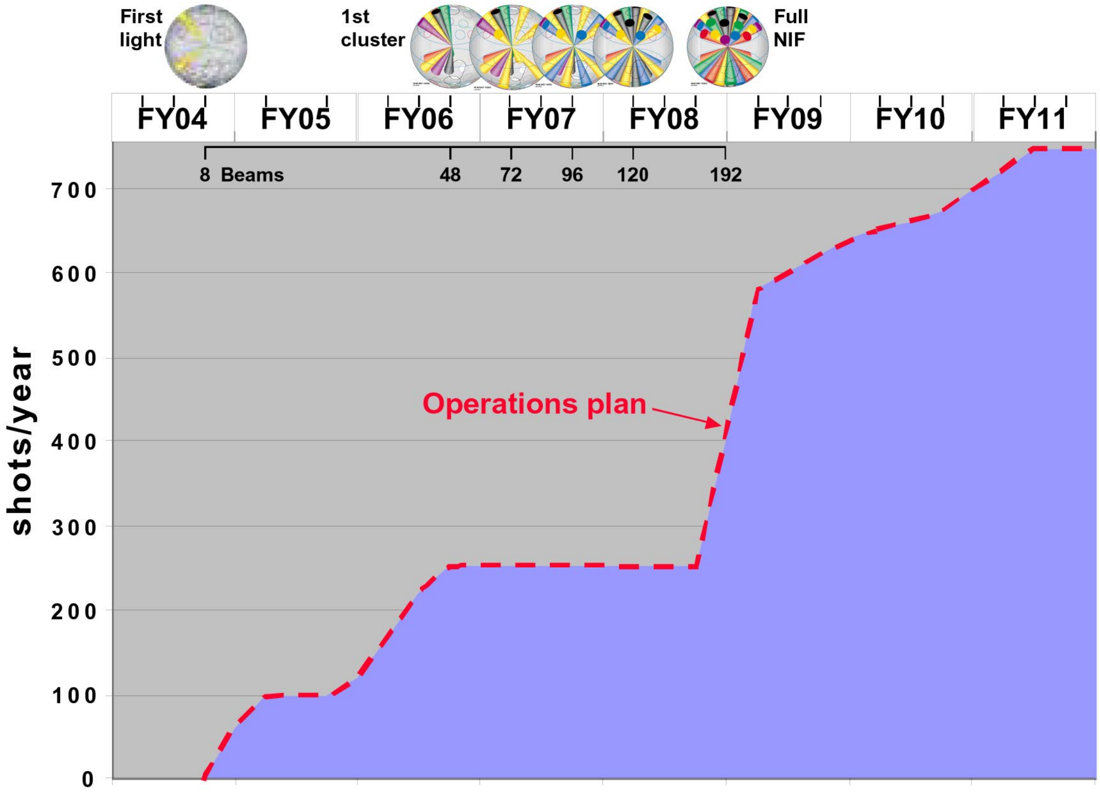


Figure E-6. Planned shot rate during the NIF deployment (prior to FY 2009) and ramping up to full operation thereafter.

E

Appendix F – Commissariat à l'Énergie Atomique Statement on High Energy Density Physics

F.1 CEA/DAM viewpoint on the importance of high energy density physics to maintain the safety, security, and reliability of our nuclear weapons

Modern thermonuclear weapons, as multi-stage energy amplifiers, involve a succession of complex phenomena, some of these with thresholds.

In the absence of nuclear tests, only the very beginning of a weapon's functioning, corresponding to the high explosive regime, can be addressed through fully representative experiments (hydrodynamics shots, including sub critical experiments). Therefore, numerical simulation is essential for fully assessing the impact of modifications, even minor, on a given weapon's design, as compared to an already tested reference one. Such modifications are unavoidable for the stockpile over a long period of time, either due to aging effects to refurbishment (correction of aging effects) or induced by an evolution of constraints (safety requirements, weaponization, operating mode…).

The current numerical simulation of nuclear weapons relies in some instances on modeling adjustments between physical processes and numerical techniques. This is especially the case for nuclear phases of functioning, corresponding to high energy density regimes, which cumulate utmost modeling complexity and demand in computing resources. This situation is, at least for the time being, balanced by the high level of confidence put in our experienced designers judgement.

The decline over time of this judgement capacity as our designers retire implies that we significantly improve the predictive capacity of our simulation tools.

In this context, high energy density physics is of paramount importance. Access to relevant experiments in this area is essential for three main reasons. It is necessary

- to limit the uncertainty on physical constants, opacities and equation of states (high densities and high temperature range) are important themes for this first category.

- to improve/build and validate models for some of the phenomena involved in weapon functioning.

  Several physical phenomena are presently inadequately modeled, or at least require additional experimental validation:

- emission and transport of photons in complex systems associating opaque and transparent media,
- turbulent mixing at high Reynolds numbers in hot and dense plasmas,
- nuclear physics at high densities and high neutron fluxes,
- thermonuclear combustion with mix…

- to validate "by parts" the complex numerical simulation of coupled phenomena.

Validation of numerical simulation coupling these different phenomena cannot be obtained solely by confrontation with a limited set of past nuclear tests data. Moreover measurements performed in these experiments were too global to allow a step by step control of the simulation. New specific validation experiments "by parts" are thus necessary. These experiments should involve coupling of relevant phenomena in a similar way to weapons, for example:

- radiation hydrodynamics,
- implosion with turbulent mix,
- implosion and thermonuclear burn…

Nevertheless, to DAM opinion, limiting experimental high energy physics to measurement of some constants (opacities) and access to a limited class of phenomena (NLTE plasmas for example) will not be sufficient for fully validating numerical tools and providing new designers with the adequate judgement capacity for future certification even with robust weapons. Reaching the ignition regime is necessary for this objective.

F.2 CEA/DAM viewpoint on the role that the CEA/DOE collaboration on high energy density has played in the development of our LIL and LMJ laser facilities

The current collaboration between CEA and DOE deals with:

- the technology R&D required to construct and operate the US National Ignition Facility (NIF) and the French Laser Megajoule (LMJ) and its 8-beam Engineering Prototype (the Ligne d'Integration Laser – LIL),
- certain aspects of the actual construction activation and operation of the facilities, and

- unclassified high energy density physics on existing and future facilities.

It is carried out under a ten-year government to government agreement on "Cooperation in Research, Development and Applications of High Energy Lasers and High Energy Laser-Matter Interaction Physics" signed on August 9, 1994.

The LIL and LMJ projects have benefited significantly from the joint research and technology development activities in this program. During the 80's and early 90's LLNL/DOE had invested significantly more in megajoule laser technology than CEA. Consequently, until approximately 1997, CEA concentrated on achieving a parity state in megajoule laser technology. The equilibration process took the form of technology and know-how transfer from LLNL/NIF activities in form of direct funding for technology R&D and/or equipment, codes and personnel supplied by CEA for joint activities at LLNL. An equivalent amount was provided by LLNL. The joint R&D activities included: validation of full-aperture multi-pass NIF and LMJ architecture with the Beamlet facility, testing and validation of NIF/LMJ amplifier hardware, rapid growth crystal technology, plasma electrode Pockels cell, code development and optics damage thresholds. An additional $60 M spent at the laser glass vendors to develop the continuous-pour laser amplifier slab technology was also shared between LLNL/NIF and CEA.

After the proof of principle phase in optics and physics on Beamlet, the LIL facility under completion in France at CESTA will be used as an engineering prototype for the LMJ facility. LLNL/NIF personnel will participate in several aspects of the construction, integration and activation of LIL this year, with the first laser shots planned at the end of 2001. LLNL personnel will also take part in the laser and experimental activities in 2002. Their objective is to bring the LIL laser at its nominal energy level (7.5 kJ/beam) with the beam quality at the focal spot required for high energy density experiments. In addition to providing valuable assistance to the LIL/LMJ project this will also provide early evaluation and validation of several key NIF technologies.

The collaboration has been very effective in the high energy density physics area. Together with LLNL, LANL and the University of Rochester, a large number of joint DOE/CEA experimental campaigns were carried out on Nova and Phebus prior to their shutdown in 1999. The joint experimental campaigns are continuing on Omega. Over the last two years, a program was started to develop common NIF/LMJ diagnostics and cryogenic target support equipment.

F.3 CEA/DAM viewpoint on the value of achieving ignition and burn in order to maintain your stockpile without returning to underground testing

Achieving ignition and burn is a critical objective for France's Simulation Program, for two reasons:

1. Together with numerical simulation, a laser enabling scientists to design and perform burn experiments is the only tool allowing France to maintain the level of expertise of its designers at the right level.

More precisely, our current designers were trained being first apprentices, coached by already certified designers. Designers would go through a cycle of design, prediction, experimentation with a nuclear test, and interpretation, before applying this methodology by themselves. It is crucial that future designers be trained in a similar way. Therefore, they have to be confronted with the same kind of highly complex physics that one encounters in weapons physics. Moreover, they have to learn how to confront numerical simulations and experiments to build up their own judgement. Only a facility allowing for ignition and burn can fulfill these requirements:

- It offers the same level of complexity regarding physics. The design of ignition and burn experiments requires simulations involving many coupled physics models, and the capacity to reach calibrated energy levels, themselves beyond specific thresholds;

- The methodology used for performing experiments is similar to the one that was used for nuclear tests (modeling/numerical prediction/experiments/interpretation cycle);

- Ignition physics is close enough to weapons physics.

2. Ignition and burn will allow our scientists to tackle specific weapons physics problems that couldn't be looked at otherwise. Actually, there are three types of experiments that can be performed on a Megajoule class laser. The two last types depend critically on achieving ignition:

- Physical constants determination (e.g. opacities, Equation of State, …). Obtaining more precise values in the appropriate parameter range will eliminate a set of adjustment techniques that designers currently use.

- Experiments addressing modeling issues that need to be improved. We refer here to what we call "validation by parts" of the physics models contained in our design codes. Designing experiments on the French Megajoule laser that will be useful to weapons physics can be translated into the following question: "How to identify partial self-similarities between LMJ physics and weapons physics." Such an analysis concludes that achieving ignition and burn are critical to a number of issues relevant for weapons physics:

  - High Reynolds number turbulent flows cannot be produced by current lasers. High enough Reynolds numbers flows require energies of the Megajoule laser class, and ignition for mix studies;
  - Non stationary radiation transfer plays an important part in weapons physics. Although numerous experiments can obviously be performed with either current or more advanced lasers, reproducing specific time scale ratios requires lasers in the megajoule or higher range. Burn is required to reach these conditions;
  - Burn is obviously critical for DT combustion studies;
  - Non trivial states of matter require the full power obtained with ignition and burn for being reached.

- Integrated experiments where the designers have to solve the whole set of ignition related problems and use their acquired expertise in thermonuclear physics. They will thus gain a great level of confidence in their scientific and numerical skills. From a more technical point of view, those experiments will allow a global validation of our weapons simulation codes, developed for designing both laser and weapons configurations. More details about those integrated experiments would necessitate classified material that is not adapted to this paper.

F

Appendix G – United Kingdom Statement on High Energy Density Physics

The Role and Strategy for the Provision of High Energy-Density Physics Experimental Facilities in Support of the UK Research and Capability Maintenance Programme*

G.1 Introduction

1. The overarching objective of the UK nuclear warhead programme is to keep the Trident warhead in service, and to be able to underwrite its performance and safety over a period much longer than its originally intended service life. During this time components within the warhead will undergo aging processes, many of which are poorly understood, and some components may be replaced in refurbishment programmes. It is essential that the performance and safety of the warhead can continue to be underwritten under these circumstances. In addition, the UK is to retain the capability to design, manufacture and underwrite the performance of a successor warhead for the longer term should one be required. All of this is to be achieved without recourse to underground nuclear testing.

2. With the advent of the Comprehensive Test Ban Treaty (CTBT), the UK, in common with other nuclear weapon states, is developing science based stockpile stewardship (SBSS) programmes to enable us to continue to underwrite the performance and safety of nuclear warheads without underground nuclear tests. The programmes include the development of improved theoretical models, the exploitation of supercomputer technology and AGEX I (hydrodynamics, typically in support of primary physics) and AGEX II (high energy-density physics, typically in support of secondary physics) programmes aimed at providing data to underpin the modeling.

G.2 The Role of AGEX II

3. The AGEX II experimental programme provides vital element of the overall UK stockpile stewardship programme in three crucial areas:

   a) <u>Provision of experimental data</u>. It is essential that the improved theoretical models of warhead behaviour be underpinned by high quality data on material opacity and equation of state at relevant temperatures and pressures. In addition the models must be validated against experiments which enable dynamic problems in radiation-hydrodynamics to be studied in representative geometries.

b) Recruitment, retention and development of high calibre staff. If the long-term UK objectives are to be met, the programme must have continuing access to scientific and engineering staff of the highest calibre. In order to achieve this objective the programme must offer relevant areas of challenging work and the necessary facilities to attract and retain such staff. The plasma physics work in AGEX II is regarded as a particularly suitable area. Much of the work will be publishable in the scientific literature. Good work here will enhance the reputation of AWE in the wider technical community, encourage the flow of ideas into and out of AWE and ultimately have a beneficial effect on recruitment and retention.

c) US/UK collaboration. For many years the UK has benefited enormously from close technical dialogue with the US in the nuclear warhead area. This has given the UK access to a range of facilities (including in the past underground test facilities) and exposure to a more extensive scientific programme and database. In return we understand that the US values the independent view that a small but traditionally innovative UK programme offers. The US SBSS AGEX II programme includes a number of facilities in which high-power lasers and pulsed power machines are to be used for the generation of high temperatures and pressures. NIF is to be the cornerstone of the programme. It is vital that the UK carries out a programme of work, both independently and collaboratively, which will enable us to contribute to joint US/UK objectives and access the much larger US programme in this area. In order to do this the UK must have both a programme of work, and the high calibre staff, which will enable us to remain a credible partner in this vital relationship.

G.3 Programme Balance

4. The research and capability maintenance programme must be constructed in such a manner that there is a realistic programme work across the whole field of the development of theoretical models, exploitation of supercomputers and the underpinning hydrodynamic and plasma-physics experiments, which is directed towards the long-term objectives. The programmes must be balanced so that meaningful work can be done in a coherent way in all of the programme elements, but at the same time fitting within the available resource constraints including the ongoing maintenance of our production facilities. It is clear that for a warhead capability there must be substantial work and investment in each of the areas. Because of the limited budget, however, hard choices have had to be made on the balance of investment between programme elements.

5. A supercomputer capability which will enable AWE staff to make significant advances in modeling and to make a useful contribution to US/UK objectives will be essential. It is not possible to fund systems comparable with leading-edge ACSI technology, but the level of investment planned should enable the UK to follow US developments, albeit some years behind.

6. An indigenous AGEX I capability is essential and has traditionally been a UK strength area. A new hydrodynamic research facility (HRF) is planned for the middle of this decade. The facility will enable experiments to be fired more efficiently and will be equipped with high resolution, multi-axis diagnostics.

7. The UK must have access to high energy-density AGEX II facilities. The full 600TW power of NIF will be needed to study thermonuclear processes. At lower powers of order 100TW it will be possible to measure complex warhead processes using sophisticated scaled geometries, with supporting research carried out at still lower powers. The UK has decided that it is not affordable to build an indigenous facility of even 100TW magnitude and had decided to enter into partnership with the US to permit UK access to NIF. It is essential that the UK is able to undertake a programme that will allow it to carry out the necessary national programmes whilst remaining a credible partner for collaboration.

G.4 The Way Ahead for High Energy-Density Experiments

8. The initial plans for UK investment in NIF supported a shot rate enhancement programme (SREP) to increase the capacity of NIF to make headroom for UK experiments, provided at a later date a second target chamber for UK experiments up to 100TW and permitted occasional access to the full NIF. However increased costs and programmatic delays for NIF mean that consideration of a second target chamber is now beyond planning horizons.

9. The UK, in discussion with the US, now plans to continue with the SREP investment in return for access to NIF (formalised in a letter of 15 Nov 2000 from DOE/DP1 to the UK MOD's Chief Scientific Advisor). However to supplement access to NIF, which is now later and our investment buys us less access than originally planned, consideration is being given to identifying other facilities which the UK might use. These include OMEGA in Rochester and LIL in France. HELEN will be retained for the time being and consideration is being given as to whether modest upgrades might be a worthwhile investment.

10. In addition to the laser technology the UK has watched with interest the potential of pulse power Z at Sandia, as an AGEX II tool. This technology is evolving and appears to be making significant progress and the UK would wish to make use of it, working collaboratively with partners in the US nuclear weapon laboratories.

G.5 Conclusion

11. The UK regards experimental work on high energy density physics as essential for a comprehensive stockpile stewardship programme. Funding constraints mean that the UK will have to include access to offshore facilities, principally NIF in its strategy for stewardship of our stockpile and maintenance of capability.

Appendix H – Previous Reviews

Reviews by the National Academy of Sciences:

Review of the Department of Energy's Inertial Confinement Fusion Program, National Academy of Sciences, March 1986.

Review of the Department of Energy's Inertial Confinement Fusion Program, National Academy of Sciences, September 1990.

Review of the Department of Energy's Inertial Confinement Fusion Program – The National Ignition Facility, National Academy of Sciences, March 1997.

Reviews by the General Accounting Office:

Performance of Participants in DOE's Inertial Confinement Fusion Program, March 1990 (GAO/RCED-90-113BR).

National Ignition Facility: Management and Oversight Failures Caused Major Cost Overruns and Schedule Delays, August 8, 2000 (GAO/RCED-00-271)

Reviews by Other Groups:

Review of Science Based Stockpile Stewardship, JASON Committee, November, 1994 (JSR-94-345).

Inertial Confinement Fusion Review, JASON Committee, March 1996 (JSR-94-300).

External Independent Review of the Department of Energy National Ignition Facility Project at the Lawrence Livermore National Laboratory Site Livermore, California, Lockwood Greene, March 29, 1999.

Reviews by the Inertial Confinement Fusion Advisory Committee:

ICFAC Meeting 1, December 16-18,1992, Washington, DC.

ICFAC Meeting 2, March 8-10, 1993, Albuquerque, NM.

ICFAC Meeting 3, August 25-27, 1993, Washington, DC.

ICFAC Target Physics Subcommittee Meeting 1, October 28-29, 1993, Livermore, CA.

ICFAC Target Physics Subcommittee Meeting 2, December 15-16, 1993, Los Alamos, NM.

ICFAC Meeting 4, January 6-7, 1994, Livermore, CA.

ICFAC NIF Laser Subcommittee Meeting, April 20-21, 1994, Livermore, CA.

ICFAC Meeting 5, May 18-20, 1994, Rochester, NY.

ICFAC Meeting 6, August 2-4, 1994, Los Alamos, NM.

ICFAC Meeting 7, June 6-8, 1995, Albuquerque, NM.

ICFAC Meeting 8, November 14-15, 1995, La Jolla, CA.

ICFAC Letter Report 1, September 27, 1993.

ICFAC Letter Report 2, February 15, 1994.

ICFAC Letter Report 3, August 8, 1994.

ICFAC Letter Report 4, February 21, 1996.

DOE Reviews:

Laboratory Microfusion Capability Study Phase I, April 1989 (DOE/DP-0069)

The Nike Laser Program at the Naval Research Laboratory, February 1990.

Fusion Policy Advisory Committee, September,1990

The Nike and Mercury Programs, September 1992.

NIF Justification of Mission Need, January 1993.

Laboratory Microfusion Capability Study Phase II, May, 1993 (DOE/DP-00 1 7)

Independent Cost Estimate – The National Ignition Facility Conceptual Design, Foster Wheeler USA, May 1994 (DOE Contract No. DE-ACO 1-94PR I 00 1 6)

Approval of Key Decision One for the NIF, October 1994.

The NIF and the Issue of Nonproliferation, 1995.

NIF Title I Design Review, November 1996.

Programmatic Environmental Impact Review for Stockpile Stewardship and Management, 1996 (DOE/EIS-0236)

Independent Cost Estimate – The National Ignition Facility Title I Design, Foster Wheeler USA, January, 1997

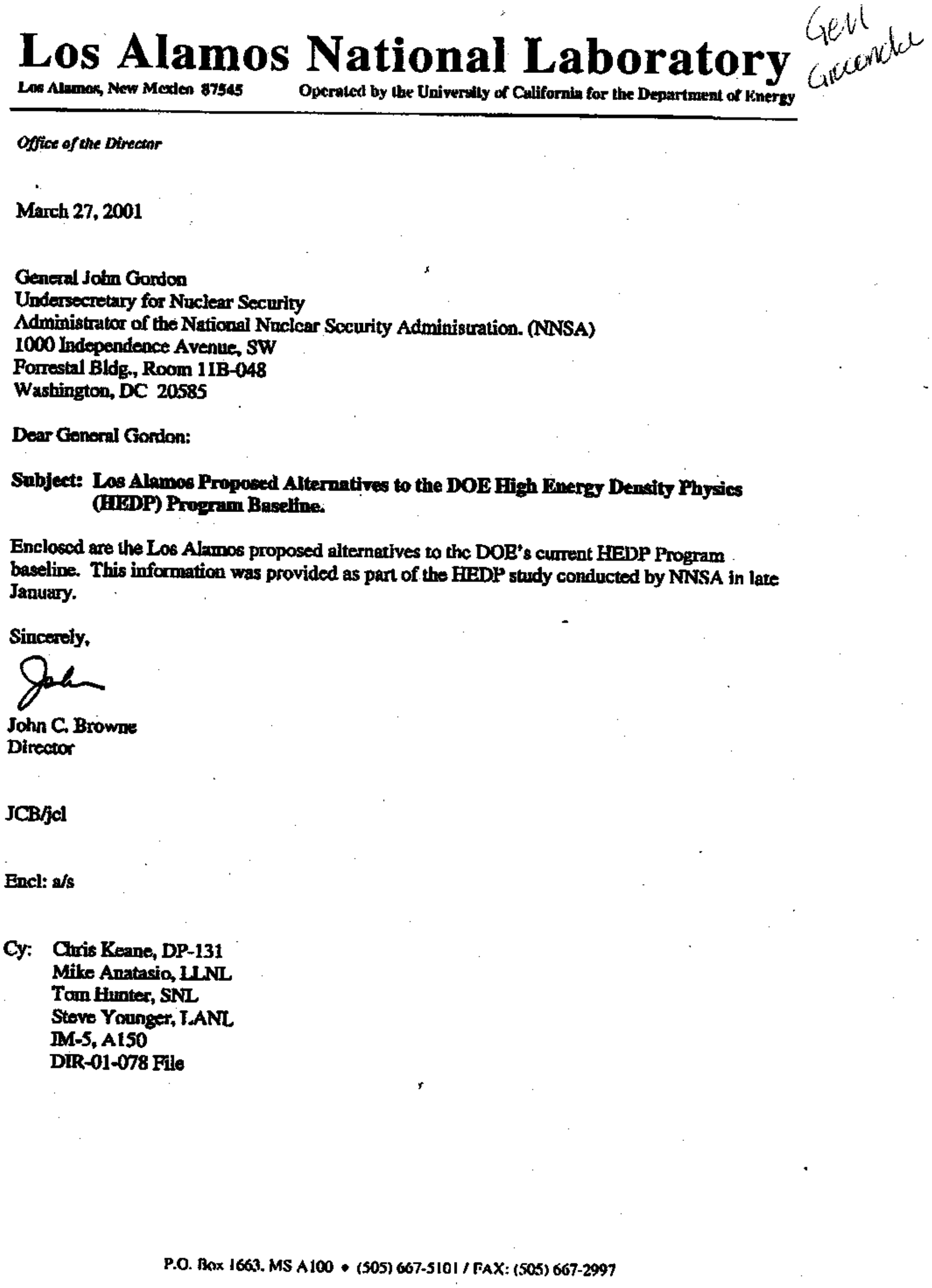
NIF Title II Design Reviews, 1997 – present.

30-Day Study of the Stockpile Stewardship Program, November 23, 1999.

Final Report of the NIF Laser System Task Force, Secretary of Energy Advisory Board, October 2000.

H

Appendix I – Laboratories Alternatives



Los Alamos National Laboratory
Los Alamos, New Mexico 87545 Operated by the University of California for the Department of Energy

Gen'l [illegible]

Office of the Director

March 27, 2001

General John Gordon
Undersecretary for Nuclear Security
Administrator of the National Nuclear Security Administration. (NNSA)
1000 Independence Avenue, SW
Forrestal Bldg., Room 11B-048
Washington, DC 20585

Dear General Gordon:

Subject: Los Alamos Proposed Alternatives to the DOE High Energy Density Physics (HEDP) Program Baseline.

Enclosed are the Los Alamos proposed alternatives to the DOE's current HEDP Program baseline. This information was provided as part of the HEDP study conducted by NNSA in late January.

Sincerely,

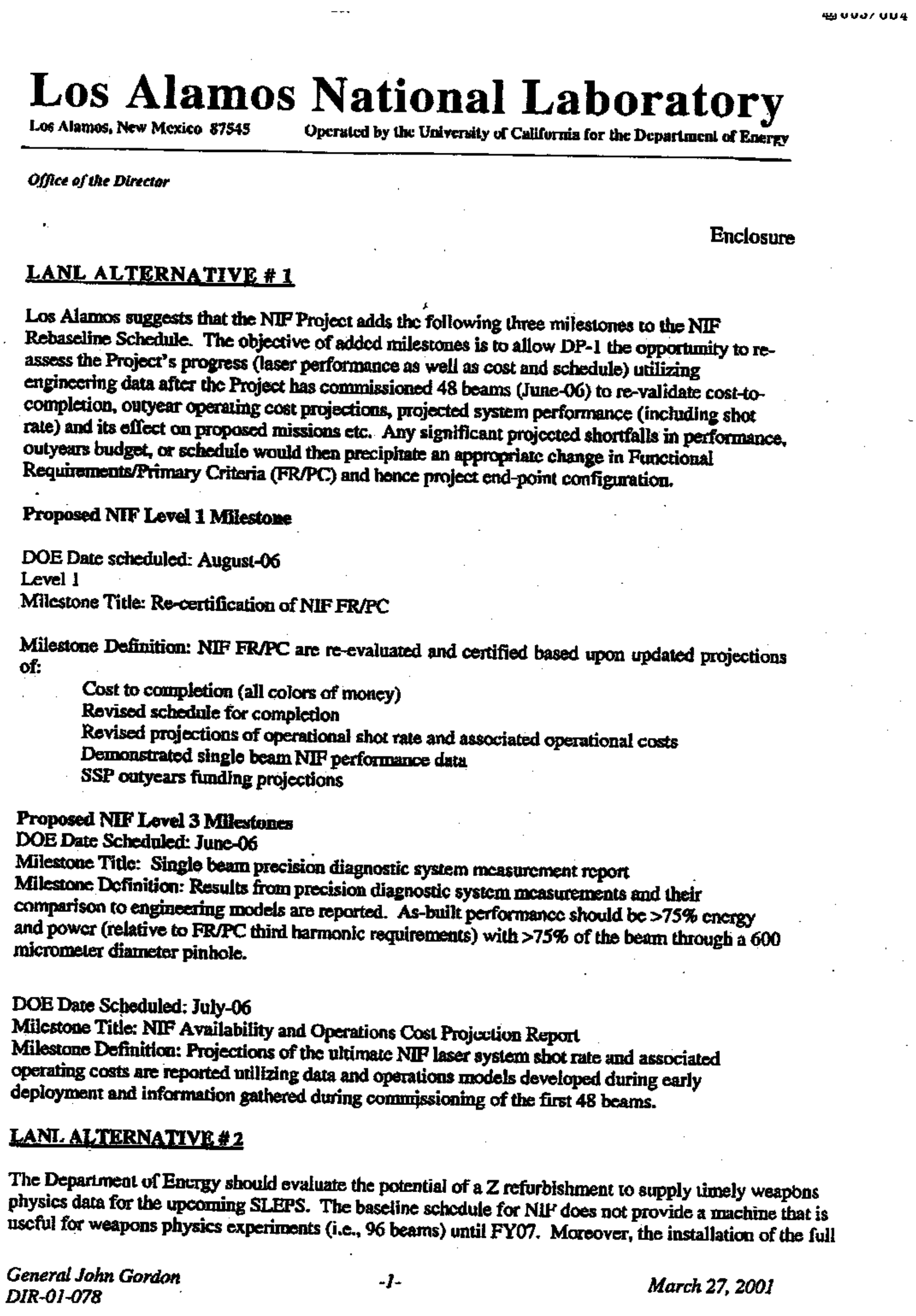
John C. Browne
Director

JCB/jcl

Encl: a/s

Cy: Chris Keane, DP-131
Mike Anatasio, LLNL
Tom Hunter, SNL
Steve Younger, LANL
IM-5, A150
DIR-01-078 File

P.O. Box 1663, MS A100 • (505) 667-5101 / FAX: (505) 667-2997



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LANL ALTERNATIVE # 1

Los Alamos suggests that the NIF Project adds the following three milestones to the NIF Rebaseline Schedule. The objective of added milestones is to allow DP-1 the opportunity to re-assess the Project's progress (laser performance as well as cost and schedule) utilizing engineering data after the Project has commissioned 48 beams (June-06) to re-validate cost-to-completion, outyear operating cost projections, projected system performance (including shot rate) and its effect on proposed missions etc. Any significant projected shortfalls in performance, outyears budget, or schedule would then precipitate an appropriate change in Functional Requirements/Primary Criteria (FR/PC) and hence project end-point configuration.

Proposed NIF Level 1 Milestone

DOE Date scheduled: August-06
Level 1
Milestone Title: Re-certification of NIF FR/PC

Milestone Definition: NIF FR/PC are re-evaluated and certified based upon updated projections of:

- Cost to completion (all colors of money)
- Revised schedule for completion
- Revised projections of operational shot rate and associated operational costs
- Demonstrated single beam NIF performance data
- SSP outyears funding projections

Proposed NIF Level 3 Milestones
DOE Date Scheduled: June-06
Milestone Title: Single beam precision diagnostic system measurement report
Milestone Definition: Results from precision diagnostic system measurements and their comparison to engineering models are reported. As-built performance should be >75% energy and power (relative to FR/PC third harmonic requirements) with >75% of the beam through a 600 micrometer diameter pinhole.

DOE Date Scheduled: July-06
Milestone Title: NIF Availability and Operations Cost Projection Report
Milestone Definition: Projections of the ultimate NIF laser system shot rate and associated operating costs are reported utilizing data and operations models developed during early deployment and information gathered during commissioning of the first 48 beams.

LANL ALTERNATIVE # 2

The Department of Energy should evaluate the potential of a Z refurbishment to supply timely weapons physics data for the upcoming SLEPS. The baseline schedule for NIF does not provide a machine that is useful for weapons physics experiments (i.e., 96 beams) until FY07. Moreover, the installation of the full

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NIF (i.e., 192 beams) could interfere with weapons physics experiments until FY09. This is not consistent with the currently planned SLEP FPU dates since the Department will not a have radiation source to evaluate possible performance issues that arise as a result of weapons refurbishment.

Sandia National Laboratories may be able provide a relatively low-cost interim radiation source that is based on a refurbishment of the Z machine. The current Z machine is 15 years old. A refurbishment of Z, which involves replacing the existing capacitors and the power flow channel, has the potential of providing a 3.6 MJ x-ray source for weapons physics experiments. Preliminary estimates indicate that the Z refurbishment could be accomplished by FY05 for less than $60M including a 25% contingency.

The Department of Energy should conduct an analysis of the physics breakpoints that could be achieved on the refurbished Z, as well as a detailed analysis of the costs of a Z refurbishment and future operating costs for the facility. Pending the outcome of this analysis and the identification of funding for this project, a refurbished Z should be added to the HEDP baseline.

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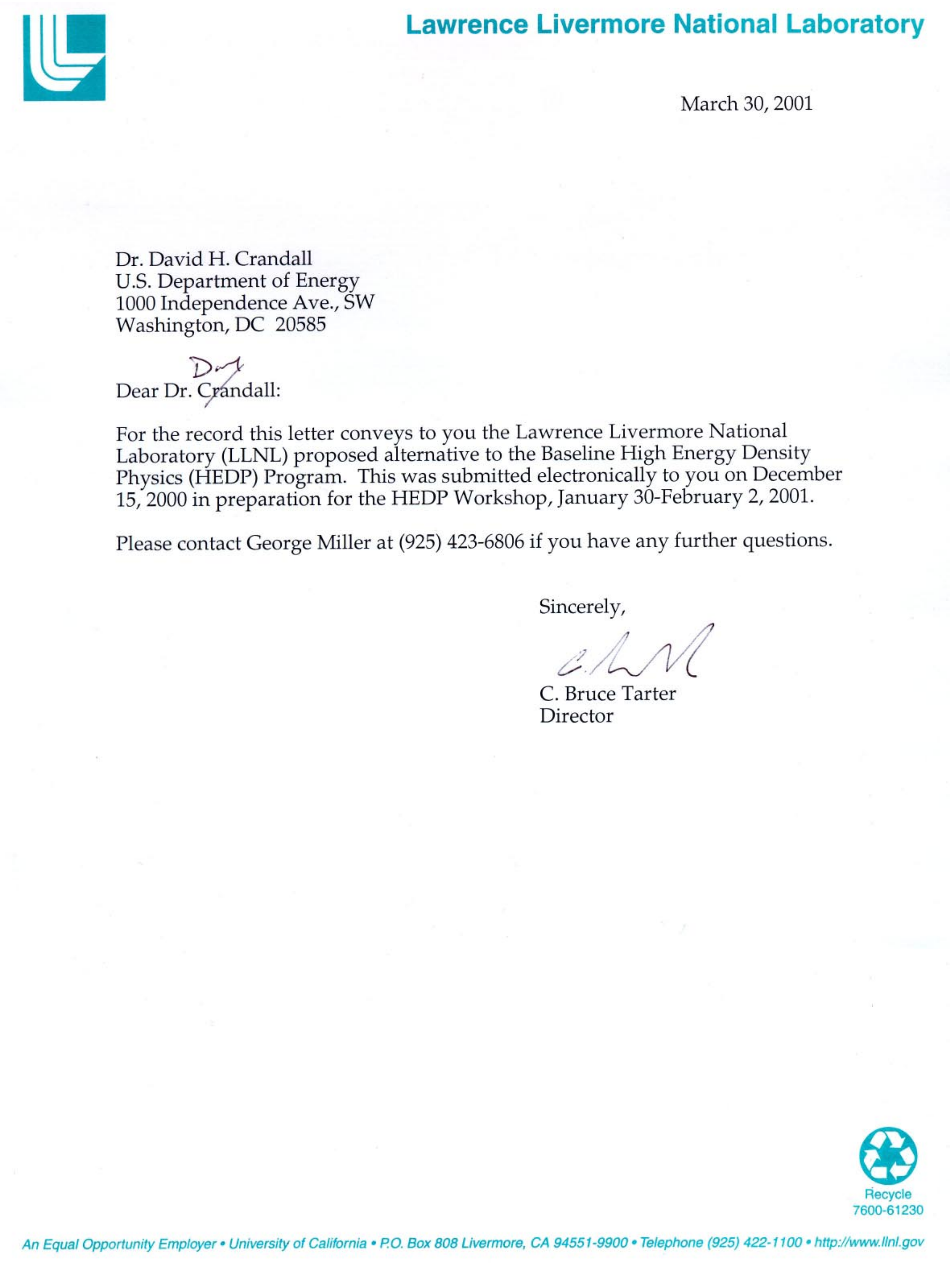

Lawrence Livermore National Laboratory

March 30, 2001

Dr. David H. Crandall
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Dr. ~~Crandall~~ Dave:

For the record this letter conveys to you the Lawrence Livermore National Laboratory (LLNL) proposed alternative to the Baseline High Energy Density Physics (HEDP) Program. This was submitted electronically to you on December 15, 2000 in preparation for the HEDP Workshop, January 30-February 2, 2001.

Please contact George Miller at (925) 423-6806 if you have any further questions.

Sincerely,

C. Bruce Tarter
Director

An Equal Opportunity Employer • University of California • P.O. Box 808 Livermore, CA 94551-9900 • Telephone (925) 422-1100 • http://www.llnl.gov

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NATIONAL IGNITION FACILITY
PROGRAMS DIRECTORATE

Chris Keane
U.S. Department of Energy, DP-131
Forrestal
1000 Independence Ave., SW
Washington, DC 20585

Dear Chris,

This letter transmits an alternative to the DOE Program Baseline, as requested by your December 12, 2000, High Energy Density Physics (HEDP) Program Baseline document. The alternative that we recommend the Department consider is an acceleration of the NIF Project by two years over its baseline plan.

We look forward to the review of this option in January.

Sincerely,

George H. Miller
Associate Director for NIF Programs

Cc:

Jim Anderson

Alternative to the DOE High Energy Density Physics Program Baseline: Accelerated NIF

LLNL NIF Programs
December 15, 2000

Introduction

The directors of the DOE Nuclear Weapons Laboratories, along with the head of DOE's Defense Programs, reaffirmed the critical role of NIF in white paper, "The National Ignition Facility and Stockpile Stewardship"

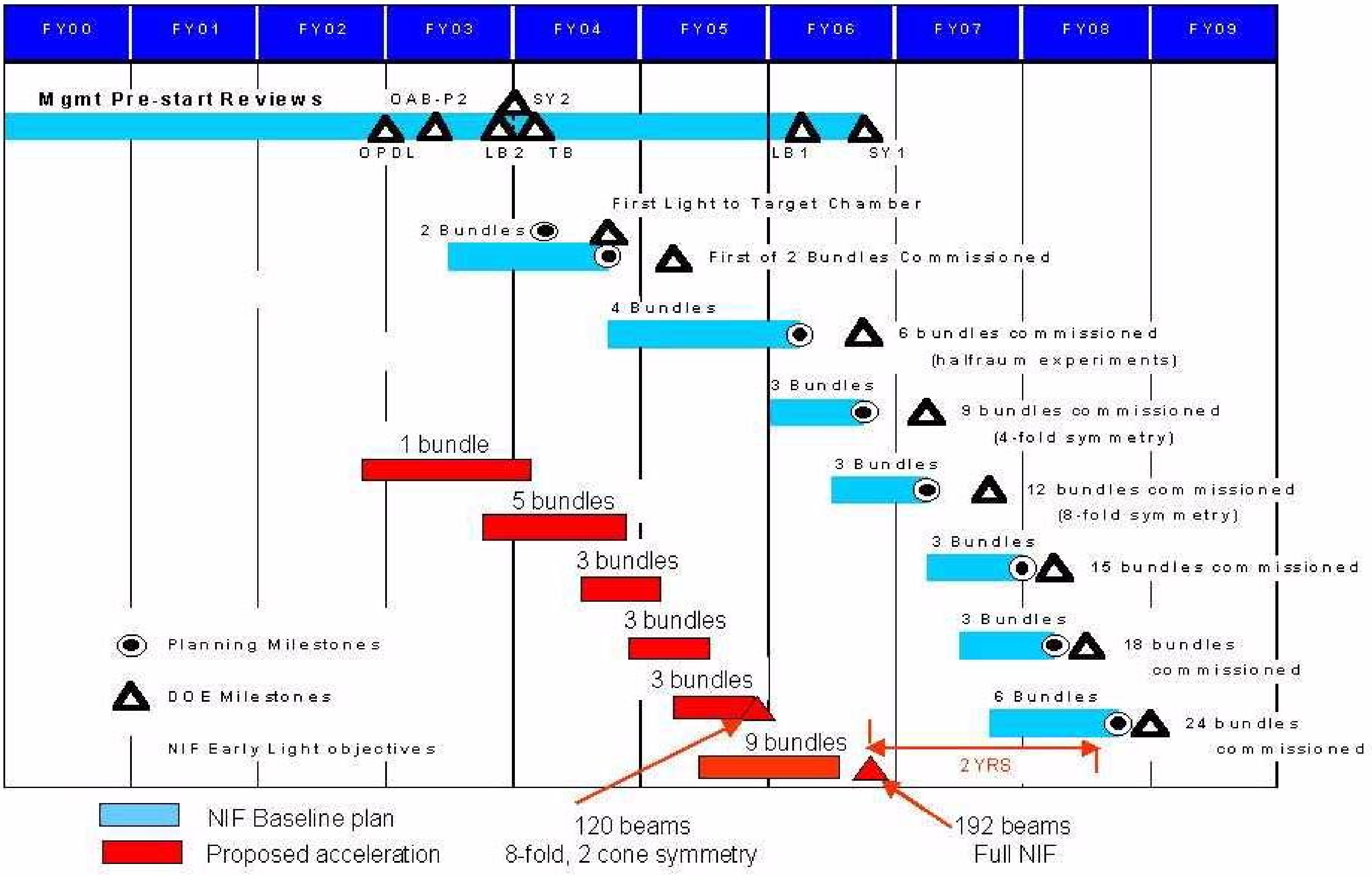
> "The NIF is an integral part of the scientific tool-kit being developed for the Stewardship program and is therefore an essential element of the SSP, the nation's program to maintain the security and reliability of our stockpile without nuclear testing. The NIF will provide important information that will improve our basic understanding of nuclear weapons and hence aid in the definition of future stockpile life extension programs. It will be an important tool for training and testing the individuals who will ultimately provide us confidence in the stockpile in the long term."

The current baseline schedule for the completion of the NIF initiates cluster (48 beam) operation and half-holraum (halfraum) stockpile stewardship experiments in late FY06. Baseline project completion, 192 beams, is scheduled for the end of FY08. This schedule is longer than is optimum for completing the project and it delivers an operating facility several years later than is desired or optimum for HEDP experiments supporting Campaigns 1, 2, 4, 7 &10 and DSW.

This proposed alternative accelerates the initiation of cluster (halfraum experiments) and completion of NIF by two years, to the end of FY04 and FY06 respectively. Accomplishing this acceleration requires increased funding profiles in FY02 through FY05. This accelerated schedule would allow capital expenditures on other Stockpile Stewardship facilities to begin in the FY05 time frame.

Attached is figure that compares the accelerated schedule (in red) with the baseline schedule (open triangles).

Fast 192-beam deployment



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Sandia National Laboratories
Operated for the U.S. Department of Energy by
Sandia Corporation

C. Paul Robinson
President and Laboratories Director

P.O. Box 5800
Albuquerque, NM 87185-0101

P.O. Box 969
Livermore, CA 94551-0969

Phone: (505) 844-7261
Fax: (505) 844-1120
Internet: cprobin@sandia.gov

December 15, 2000

Madelyn R. Creedon
Deputy Administrator
National Nuclear Security Administration
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dear Ms. Creedon:

Subject: Sandia Proposed Alternative to the DOE High Energy Density Physics (HEDP) Program Baseline

Enclosed is Sandia's proposed alternative to the DOE's baseline HEDP Program. This information is provided as input to the HEDP workshop to be held during the last week of January 2001.

Respectfully,

[original signed by C. Paul Robinson]

Enclosure

Copies to:
Dave Crandall, DP-10
Chris Keane, DP-131
Mike Anastasio, LLNL
Steve Younger, LANL
Tom Hunter, SNL

Exceptional Service in the National Interest

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Sandia National Laboratories
Recommendations for the DOE High Energy Density Physics (HEDP) Program Baseline

December 15, 2000

In Sandia's view, it is important that a comprehensive examination of the total HEDP path forward is performed and that it address:

Integrity of the Stockpile Stewardship Program (SSP)

- Understand and provide the HEDP data needed to maintain the safety, security, reliability and performance of the nation's nuclear weapons now and in the future without nuclear testing.
- Establish total system costs and clear management of cost and programmatic risk.
- Maintain active engagement with a broader scientific community and incorporate appropriate external review of management plans and significant milestone events.

Balance the HEDP program against the rest of the SSP to insure that HEDP costs and benefits are consistent with other critical nuclear weapons program needs.

- Thoroughly examine the NIF deployment baseline to determine whether a reduced NIF configuration that saves substantial construction and/or operating costs could adequately meet the needs of the SSP.
- Effectively manage the deployment risk of the NIF.

Balance the HEDP program internally to meet near and long term needs

- Provide as much data as possible this decade to support the Stockpile Life Extension Program (SLEP) and Significant Findings Investigations (SFIs).
- Include technical diversity to mitigate risk in the program.
- Provide technology options for the future of SSP and the Inertial Confinement Fusion (ICF) program.

Summary of Recommendations

Sandia recommends two changes to the current baseline. These recommendations are based on our view that other HEDP facilities are not alternatives to NIF, but with NIF form a complementary set of needed capabilities. These recommendations are discussed in summary here, with more detail provided below.

I. Plan and execute the deployment of NIF to maximize needed data and minimize programmatic costs and risk by addressing final configurations with less than 192 beams.

- Configurations of beams less than 192should be carefully analyzed and a final configuration of beams should be targeted to maximize benefit to the SSP at affordable cost.

- Deployment of the NIF to the final targeted configuration of beams (and possibly beyond) should be contingent on engineering demonstrations of laser performance, proof of physics for HEDP and ignition, validation of updated estimates for cost-to-complete and cost of operations, and external review at significant go/no-go milestones.

II. Refurbish Sandia's Z accelerator and fully utilize it to provide HEDP data this decade and beyond to support the SLEP and SFIs, the Secondary Certification Campaign, the Dynamic materials Campaign, the Nuclear Survivability Campaign, and the ICF Campaign (for high-yield fusion capsule designs and to support the NIF project).

- Refurbished Z improves precision and reliability, increases the shot rate, and increases output to address physics breakpoints that will make it even more valuable for SLEP/SFI needs.
- Refurbished Z is complementary to the NIF in that it will uniquely provide needed HEDP data throughout this decade that will be not be available from any other source.
- Pulsed power investments for HEDP preserve diversity in the HEDP program, reduce programmatic and technical risk to the SSP, and provide technology options for the future of SSP and ICF.
- Capital costs for refurbishment of Z are estimated to be about 3% of the NIF construction costs.

Assessment of the NIF Baseline

NIF has an important, acknowledged role in the SSP

NIF is one of a set of essential capabilities for SSP, but the final scope, deployment schedule, cost baseline, and impact on the balance within SSP have not been finally established. Sandia's recommendation is that the final configuration and the deployment schedule of NIF maximize the benefit to SSP at an affordable cost. Therefore, our recommendation for NIF deployment begins with the assertion that a subset of the current baseline should be targeted as the final configuration. Deployment beyond this targeted configuration is contingent on demonstration of needs of the SSP that justify the added costs.

NIF has cost and performance risks

As with any large, complex project, technical risks exist in achieving required laser performance specifications and physics performance parameters. These risks could impact the ability of NIF to eventually perform meaningful HEDP experiments and to achieve ignition. Performance levels have been established and are part of the design specification for NIF. Failure to meet one or more of these specifications may require work-arounds, retrofits, scope changes, or other adjustments that may impact the final capability and/or cost and availability of NIF. While the project appears to be addressing technical issues quite aggressively, history suggests that difficulties of this type are to be expected in deploying a large, complex facility like NIF. Risks at this point do not appear unreasonable for proceeding with NIF to some designated level of performance.

Cost risks exist in Cost-to-Complete the NIF

Obviously, any problems related to difficulty with technical performance specifications might impact cost-to-complete. In addition, cost-to-complete may be affected by unexpected increases in equipment costs, failure to achieve the expected build-out rate of one bundle of lasers per month, and/or the availability of co-investments from international partners. Furthermore, there are significant program elements, such as the NIF capsule cryogenic system, the NIF diagnostics suite, and the Direct Drive configuration, that are un-costed or only recently included in the baseline, so they introduce uncertainty in the final cost of NIF deployment. Accurate cost estimates for these issues may not be available until some portion of the facility is built. It is also possible that recently expanded contingencies may cover cost risks.

Cost risks also exist in the Cost-to-Operate NIF

The operating cost of NIF will need further resolution. The estimated operating cost has increased over the life of the project and now is more than twice the original estimate. The current operating estimate is still significantly less than historical data that suggests that operating costs of complex facilities are about 10-15% of the capital investment. This uncertainty is not likely to be resolved until operating experience is gained with a subset of the laser beams. Parameters that will be important in determining the operating cost include the shot rate, the reliability and longevity of system components, and the mean time between significant maintenance events. Demonstrating and validating operating costs on a subset of the facility will build confidence and provide opportunity to take appropriate actions if required.

Recommendation regarding NIF

Sandia proposes that the deployment of NIF be planned and executed to minimize programmatic and cost risk by addressing final configurations with less than full 192 beams.

- Initially configurations of 48 beams should be carefully analyzed as a new baseline to maximize benefit to the SSP at affordable cost. This examination should include symmetric and non-symmetric options that are not currently in the baseline plan. If it is concluded that a higher baseline is necessary, a 96 beam configuration could be targeted as a new baseline.
- The deployment of the NIF to the targeted configuration should be phased to include specific engineering demonstrations that address milestones for laser performance, proof of physics for HEDP and ignition, validation of updated estimates for cost-to-complete and cost of operations, and external review at significant go/no-go milestones. These milestones should occur at subsets of the targeted configuration to minimize cost and technical risk.
- When the targeted configuration is reached, a decision to go beyond that level should be based on an externally reviewed demonstration of needs of the SSP that justifies the added costs.
- All planned deployment paths should include provisions not-to-preclude eventual build to 192 beams.

LLNL is best qualified to estimate the cost and schedule impact of the NIF deployment path recommended here. Therefore, we have not provided cost and schedule data for this portion of our proposal. LLNL and LANL are best qualified to assure the impact of a targeted configuration on weapons physics benefits.

Pulsed Power Investments to Balance the HEDP Program

The risk to the HEDP Program should be balanced by diversified investments in Pulsed Power and other HEDP capabilities

- OMEGA, ATLAS, and Z all provide important capabilities to support stockpile needs and to attract and retain scientific and engineering talent for stockpile stewardship. These facilities should be appropriately supported in the HEDP program.

- In particular, Z and OMEGA will provide most of the HEDP data to support SLEP during this decade, and the technical diversity they represent for the HEDP program is an important element in preserving the vigor, vitality, and innovation needed for stockpile stewardship.

Today Z provides a unique capability to the DOE/NNSA and basic science communities

Routine operations are producing x-ray power and radiated x-ray energy more than 5 and 50 times, respectively, greater than any other laboratory device (>200 TW and 1.8 MJ). Sandia continues to utilize this capability for unique weapons science experiments and diagnostics in support of HEDP and SSP. Recently, Sandia has developed a technique using the magnetic pressure associated with the high currents on Z for isentropic compression experiments (ICE) and for launching flyer plates to previously unachieved velocities. Pressures of 2.5 Mbar have been achieved on Z with ICE and 5 Mbar with flyer plates, although about 20 Mbar should be possible using flyer plates using the present magnetic drive configuration on Z. This work has attracted worldwide attention from the shock physics and condensed matter communities and is addressing critically important HEDP issues for the Dynamic Materials Campaign.

In general, pulsed power drivers are complementary to laser drivers

- Systematic errors that may be related to the driver technology can be addressed in common research areas such as radiation flow, radiation hydrodynamics, instability and mix, moderate temperature opacities, and EOS at moderate pressures. Lasers provide unique environments for experiments that require precision pulsed shaping, high radiation temperature, and ultrahigh pressures. Pulsed power drivers provide unique experimental environments for radiation effects, material properties (ICE and flyer plates), and experiments that require large areas driven for relatively long times or multiple simultaneous experiments.
- Programmatically, Z is a complementary capability to the NIF; it will provide needed HEDP data throughout this decade and beyond that will be not be available from any other source, and it provides an avenue to preserve technical diversity in the HEDP program. Furthermore, Pulsed Power investments preserve technical options in the 2008-2010 time frame for a next generation high yield facility.

Recommendation for a Refurbished Z

Sandia recommends an upgrade to the existing Z machine as an addition to the HEDP Baseline. An opportunity exists to refurbish Z at modest cost to improve its precision and reliability, increase the shot rate, and increase its output to address physics breakpoints that will make it even more valuable for SLEP/SFI needs in this decade and beyond.

Elements of Refurbished Z

- Refreshing the 15 year old technology in Z will permit increasing delivered current to a wire array load from 20 to 26 MA.
- Improved pulse shape and pulse width control can be achieved for ICE and flyer plate experiments, along with a significant increase in precision and reproducibility.
- Refurbishment will occur within the existing building with minimal impact to Z's availability while being refurbished.
- Renovating Z can be completed in FY05 in time to support the Stockpile Life Extension Program (SLEP) needs at a project cost of about $60 million. Refurbished Z will add significant and unique capability to the SSP for a modest capital investment (about 3% of the NIF construction cost).

Performance enhancements with Refurbished Z in relation to existing capability

As shown below, the performance parameters for Refurbished Z will provide the ability to access physics regions of HEDP even more relevant to weapons science.

Capability	Z (Today)	Refurbished Z (2005)
Radiated energy	1.8 MJ	3 MJ
X-ray Power	230 TW	350 TW
Temperature for Weapon Physics (VH/DH)	150/220 eV	170/250 eV
Temperature for ICF (VH/DH)	80/180 eV	90/205 eV
Pressure for ICE/Flyer-Plate	2.5/5 Mbar	10/35 Mbar
In-band energy (1 keV/5 keV/8 keV)	400/125/10 kJ	700/350/30 kJ
Legend: VH-Vacuum Hohlraum	DH-Dynamic Hohlraum	

The table below provides estimates of the operating (RTBF) and capital cost and schedule of refurbishing the Z accelerator. Prior to the HEDP review, Sandia will develop more detailed estimates and get an outside review. Dollars are in millions. Refurbished Z RTBF assumes an increase in shots from the current under-utilization of about **180 shots/yr** to full utilization of **400 /yr**. Since cost/shot is expected to be no more than the current Z, RTBF for Refurbished Z scales approximately as the number of shots/yr. Increases in Campaign costs for program activities are not shown.

	FY01	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10
Capital		10.0	25.0	25.0						
Baseline RTBF for Z	6.4	6.6	6.8	7.0	7.2	7.4	7.6	7.9	8.0	8.4
RTBF for Refurbished Z	6.4	8.3	10.0	10.6	12.2	13.7	14.0	14.5	15.0	15.4

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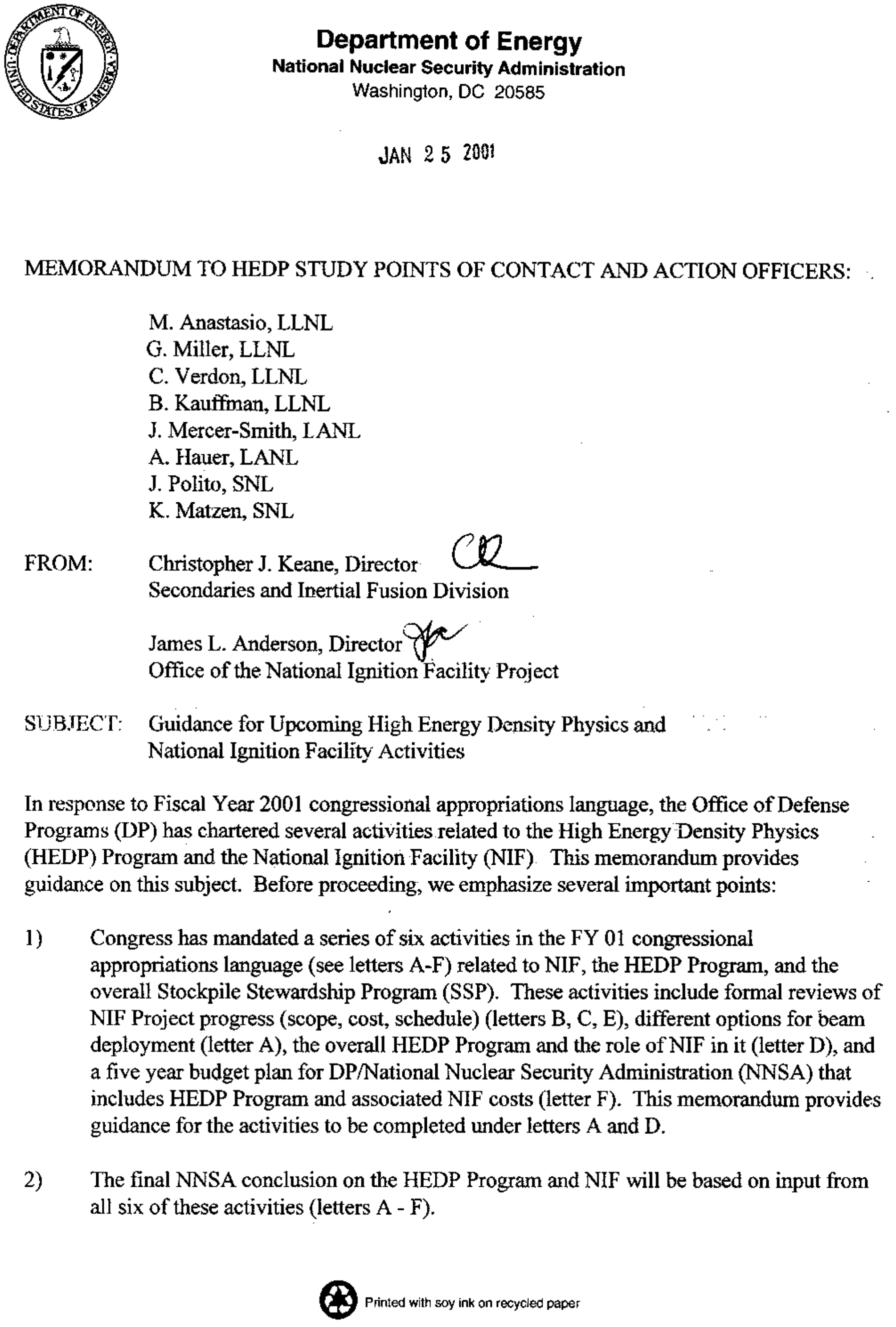
Appendix J – Alternatives Guidance Letter



Department of Energy
National Nuclear Security Administration
Washington, DC 20585

JAN 2 5 2001

MEMORANDUM TO HEDP STUDY POINTS OF CONTACT AND ACTION OFFICERS:

M. Anastasio, LLNL
G. Miller, LLNL
C. Verdon, LLNL
B. Kauffman, LLNL
J. Mercer-Smith, LANL
A. Hauer, LANL
J. Polito, SNL
K. Matzen, SNL

FROM: Christopher J. Keane, Director
Secondaries and Inertial Fusion Division

James L. Anderson, Director
Office of the National Ignition Facility Project

SUBJECT: Guidance for Upcoming High Energy Density Physics and National Ignition Facility Activities

In response to Fiscal Year 2001 congressional appropriations language, the Office of Defense Programs (DP) has chartered several activities related to the High Energy Density Physics (HEDP) Program and the National Ignition Facility (NIF). This memorandum provides guidance on this subject. Before proceeding, we emphasize several important points:

1) Congress has mandated a series of six activities in the FY 01 congressional appropriations language (see letters A-F) related to NIF, the HEDP Program, and the overall Stockpile Stewardship Program (SSP). These activities include formal reviews of NIF Project progress (scope, cost, schedule) (letters B, C, E), different options for beam deployment (letter A), the overall HEDP Program and the role of NIF in it (letter D), and a five year budget plan for DP/National Nuclear Security Administration (NNSA) that includes HEDP Program and associated NIF costs (letter F). This memorandum provides guidance for the activities to be completed under letters A and D.

2) The final NNSA conclusion on the HEDP Program and NIF will be based on input from all six of these activities (letters A - F).

3) The HEDP Program study (letter D) should have a program-oriented outcome, meaning it should clearly describe the extent to which the baseline HEDP Program and suggested alternatives meet or don't meet the needs of the SSP. We have received this guidance explicitly from both senior DP and NNSA management.

4) On December 15, 2000, alternatives to the current HEDP baseline were received from LLNL, LANL, and SNL. The baseline HEDP Program and these alternatives will be discussed at the HEDP Workshop (January 29 - February 2, 2001) at Sandia-Livermore. With respect to NIF, the alternatives submitted by LANL and SNL included the addition of a series of laser performance milestones. The appropriate venue for formal consideration of these laser milestones is the NNSA instituted NIF Project review process that will provide an ongoing assessment of Project scope, cost, schedule, and performance.

5) NNSA should assess an essentially identical set of options from both the NIF Project (letter A) and the HEDP Program (letter D) perspective. By "essentially identical" we mean that NIF related costs for the program alternatives described under 3) below may be derived from the cost estimates prepared under 1) below. This is necessary in order for NNSA to be able to respond to the letter F mandate regarding the overall SSP budget.

It is evident that the letters A-F activities must be coordinated. In particular, the guidance regarding the response to letters A and D of the congressional language is as follows:

1) In response to letter A, the NIF Project should provide assessments of the following deployment alternatives:

   a) 48 beams + 3 year pause + finish Project to 192 beams
   b) 96 beams + 3 year pause + finish Project to 192 beams
   c) 120 beams + 3 year pause + finish Project to 192 beams
   d) 192-beam accelerated schedule
   e) 192-beam baseline with "off-ramps"

   In preparing these options, assume completion of the full beampath infrastructure system (BIS) and procurement of all manufacturing sensitive items. In all cases, the planning basis will remain the current 192-beam baseline, and an active decision implemented via the change control process will be required to change that baseline. For cases a) - c) no special equipment beyond the full BIS, the manufacturing sensitive items and that required for the initial phase (48, 96 or 120 beams) will be procured. For case e), the "off-ramps" are the major project milestones that indicate satisfactory progress toward completion of the Project.

   For each case considered above, the NIF Project should provide a revised cost and schedule, and explicitly define cost and schedule deltas from the current NIF baseline.

A status report on the costing of these alternatives should be available at the HEDP Workshop. (Basic cost information on the baseline, including cost profiles for the BIS and procurement sensitive items, should also be available.) The full costing exercise should be completed by the next major NIF Project status review, currently scheduled for late February.

2) The additional laser performance milestones proposed by LANL and SNL will be formally considered for inclusion in the NIF Project at the next Project status review in late February. For information purposes, a summary of the basis for the current operations cost shown in the Project Data Sheet and the plans included in the current NIF Project baseline for demonstration of laser performance should be presented at the HEDP Workshop. LANL and SNL should also present a short summary of their proposed laser performance milestones at the Workshop.

3) In response to letter D, at the HEDP Workshop each lab should discuss the current HEDP baseline program and how their suggested alternative(s) will (or will not) meet the needs of the SSP. Each lab should start by discussing their view on how certification is to be accomplished, and then continue with a discussion of what that implies for the HEDP Program mission, strategy, goals, and objectives. Lab presentations should address the questions in the "Questions to the Study Panel Members" document.

The alternatives to be considered, along with the proposing laboratory, are listed below:

a) HEDP baseline, with NIF terminated at a single cluster (along the current baseline) (SNL)
b) HEDP baseline, with NIF terminated at 96 beams (along the current baseline) (SNL)
c) HEDP baseline, with NIF terminated at 120 beams (along the current baseline) (LANL/SNL)
d) HEDP baseline, with a 3 year pause at 96 beams to assess the probability of indirect drive ignition and impact of additional beams on the SSP (beam deployment profile as per 1b) above) (SNL)
e) HEDP baseline program, with a 3 year pause at 120 beams to assess the probability of indirect drive ignition and impact of additional beams on the SSP (beam deployment profile as per 1c) above) (SNL)
f) Add refurbishment of Z to HEDP baseline (LANL/SNL)
g) Add refurbishment of Z to cases a), b), d), and e) above (SNL)
h) Add refurbishment of Z to case c) above (LANL/SNL)
i) HEDP baseline program, with accelerated NIF (LLNL)

4) Each lab is free to comment on the alternatives submitted by the other labs. However, to ensure that every case is covered, LLNL and LANL should address from a programmatic (i.e., weapons physics) standpoint all of the alternatives listed above. SNL is required to formally report only in the area of nuclear weapons effects (as this is the area of their mission responsibility within the HEDP Program).

Thank you for your assistance. We look forward to continuing to work with you on this important subject. Please contact us if you wish to discuss this further.

cc: T. Gioconda, DP-1
D. Crandall, DP-10
J. Van Fleet, DP-13
J. Anderson, DP-7
T. Hunter, SNL
S. Younger, LANL
S. Samuelson, DOE/OAK
A. Levy, DP-7
M. Cray, DP-131
H. O'Brien, DP-13
T. Batuyong, DP-131
W. Kirchner, DP-7
S. Binkley, DP-10
D. Rubin-Bice, DP-10
B. Tarter (LLNL)
J. Browne (LANL)
P. Robinson (SNL)

Appendix K – Glossary and Acronyms

µm	micrometer = one millionth of a meter
Å	Angstrom, unit of length equal to 10^{-10} meters
A	ampere
ADAPT	Advanced Design and Production Technologies – a Campaign in the SSP
AEC	Atomic Energy Commission
AGEX	aboveground experiment
AHF	Advanced Hydrodynamics Facility
ampere	the electrical current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newtons per meter of length
ASC	Advanced Simulation and Computing
ASCI	Accelerated Strategic Computing Initiative
Atlas	a pulsed-power facility at LANL
AWE	Atomic Weapons Establishment
B53	a thermonuclear gravity bomb formerly employed on U.S. Air Force aircraft that was retired in 1997, when the B61-11 entered the stockpile
B61	a thermonuclear gravity bomb employed on U.S. Air Force and NATO aircraft
backlighter	Strong radiation source used during experiments to facilitate imaging of targets. In laser systems, some of the beams may be designated as backlighter beams and aimed at a suitable material to produce the radiation necessary to illuminate the target for diagnosis.
bar	A unit of pressure equal to 100,000 pascals, approximately equal to 0.98692327 atmosphere or 14.5 pounds per square inch
bremsstrahlung	literally “braking radiation,”typically produced by electrons as they slow down in a material
Campaigns	technically challenging, multi-year, multifunctional efforts conducted across the NNSA national laboratories, the production plants, and the test site
CCD	charge-coupled device

CEA	Commissariat à l’Énergie Atomique
CEG	Centre d’Études de Gramat
CESTA	Centre d’Etudes Scientifique et Techniques d’Aquitaine
CLWR	commercial light water reactor
cm	centimeter, unit of length equal to a hundredth of a meter
cocktail mixture	mix of high-Z materials used in hohlraums to improve the efficiency of conversion of laser light into x-rays
CTBT	Comprehensive Test Ban Treaty
D_2	diatomic deuterium
DAM	Direction des Applications Militaire within the CEA
DARHT	Dual-Axis Radiographic Hydrodynamic Test Facility
DGA	Délégation Général pour l’Armement
DoD	Department of Defense
DOE	Department of Energy
DP	Office of Defense Programs
DSW	Directed Stockpile Work
DT	deuterium-tritium
DTRA	Defense Threat Reduction Agency
Electra (at NRL)	a laser at NRL
eV	Electron volt – the energy acquired by an electron falling through a potential difference of 1 volt, approximately 1.602×10^{-19} joules
EOS	equation of state
EUV	extreme ultraviolet
filamentation	degradation of the quality of laser beams as they pass through material, due to self-focusing, which results in the creation of local hot spots or “filaments”
fluence	integral of neutron and photon flux and time, usually expressed in units of particles per square centimeter
FY	fiscal year
GA	General Atomics, Inc.

gauss	a unit of magnetic flux density equal to 0.0001 volt-second per meter^2, or 0.0001 kg·s^{-2}·A^{-1}
GJ	Gigajoule = one billion (10^9)joules
halfraum	portion of a hohlraum, typically cylindrical in shape, which is illuminated only at one end
H_2	diatomic hydrogen
HD	a molecule of hydrogen (H_2) in which one of the atoms is deuterium
HE	high explosive
HED	high energy density
HEDP	high-energy-density physics
Helen	a .9-kJ, 1-TW pulsed laser at the UK Atomic Weapons Establishment
henry	a measure of inductance equal to 1 kg·m^2·s^{-2}·A^{-2}
HEU	highly enriched uranium
hohlraum	Literally “empty space,” a cavity that absorbs and reemits radiation, ideally as blackbody radiation. Hohlraums are used in ICF experiments to create highly symmetric radiation sources.
HRF	Hydrodynamic Research Facility
Hz	hertz, a unit for frequency, measured in s^{-1}
ICE	isentropic compression experiment
ICF	inertial confinement fusion
ICFAC	Inertial Confinement Fusion Advisory Committee
IFE	inertial fusion energy
ISI	induced spatial incoherence
J	joule
Janus	a laser at LLNL
joule	a unit of energy equal to the work done when a force of one Newton acts through a distance of one meter
K	Kelvin, the unit of thermodynamic temperature equal to 1/273.16 of the thermodynamic temperature of the triple point of water.
KCP	Kansas City Plant

KDP	potassium dihydrogen phosphate
keV	1,000 eV
kG	1,000 gauss
kilogram	1,000 grams, the unit of mass equal to the mass of the international prototype of the kilogram
kJ	Kilojoule = 1,000 joules
KrF	krypton fluoride
K-shell	in quantum theory, the innermost electron orbit
LANL	Los Alamos National Laboratory
LASNEX	a software simulation tool
LEH	laser entrance hole
LEP	Life Extension Program
LIL	Laser Integration Line, a CEA pilot laser
LLCE	limited-life component exchange
LLNL	Lawrence Livermore National Laboratory
LMJ	Laser MegaJoule, a 240-beam, 1.8 MJ ICF facility being developed by the CEA
LRU	line replaceable units
L-shell	in quantum theory, the second orbit in which electrons exist
m	meter
MA	mega-ampere = 1 million amperes
Mbar	mega bar = 1 million bars
Mercury	a laser at LLNL
MESA	Microsystems and Engineering Sciences Applications Complex – a proposed microsystems development and production facility at SNL, under consideration by the NNSA
meter	A unit of length equal to the distance a photon would travel in one second, in a vacuum
MeV	million eV
micron	millionth of a meter
MJ	megajoule = million joules

MOD	Ministry of Defence
MV	megavolt = million volts
nanosecond	one trillionth (10^{-9}) of a second
NAS	National Academy of Sciences
Nd	neodymium, a chemical element
NEPA	National Environmental Protection Act, P.L. 91-190
newton	unit of force required to accelerate a 1-kilogram mass one meter second^{-1}
nH	nano henry = one billionth of a henry
NIF	National Ignition Facility, an ICF laser being constructed at LLNL
Nike	a laser at NRL
NLTE	non-local thermal equilibrium
nm	nanometer = one billionth (10^{-9}) of a meter
NNSA	National Nuclear Security Administration
Nova	a laser facility at LLNL that was decommissioned in 1999
NPT	Non-Proliferation Treaty, entered into force in 1970
NRL	Naval Research Laboratory
ns	nanosecond = one billionth (10^{-9}) of a second
NTS	Nevada Test Site
NWSP	Nuclear Weapons Stockpile Plan
OBES	Office of Basic Energy Sciences
OFES	Office of Fusion Energy Science
Omega	a laser facility at University or Rochester's Laboratory for Laser Energetics
pascal	a unit of pressure equal one newton per meter^2
PBFA	Particle Beam Fusion Accelerator
PC/FR	Primary Criteria/Functional Requirements
petawatt	quadrillion (10^{15}) watts
pit	fissile material used in a primary
P.L.	Public Law

primary	first stage of a thermonuclear weapon that provides the energy to detonate the secondary
Proto II	a second-generation pulsed-power device
ps	picosecond = one trillionth (10^{-12}) of a second
R&D	research and development
RTBF	Readiness of Technical Base and Facilities
SAIC	Science Applications International Corporation
Saturn	a pulsed-power facility at SNL
SBS	stimulated Brillioun scattering
SBSS	Science-Based Stockpile Stewardship
SC	U.S. DOE Office of Science
secondary	The second stage of a thermonuclear weapon that is detonated by the primary
SFI	Significant Finding Investigation
SGEMP	System-generated electromagnetic pulse
SLBM	submarine-launched ballistic missile
SLEP	Stockpile Life Extension Process
SNL	Sandia National Laboratories
SNM	special nuclear material
SRS	stimulated Raman scattering
SSD	smoothing by spectral dispersion
SSP	Stockpile Stewardship Program
STS	stockpile-to-target sequence
SuperMite	a first-generation pulsed-power device
SUN	Successful Use of Nova
TIM	ten-inch manipulator
Tpa	tera pascal = trillion pascals
TPC	total project cost
TW	terawatt = trillion (10^{12}) watts

UK	United Kingdom
ultrafast pickets	the technique of using a train of ultrafast pulses of laser light to increase both the beam-to-beam power balance and the frequency-conversion efficiency
UR/LLE	University of Rochester / Laboratory for Laser Energetics
UV	ultraviolet
volt	A unit of electric potential difference or electromotive force equal to one watt per ampere
VH	vacuum hohlraum
W	watt, a unit of power or radiant flux equal to one joule per second
W76	thermonuclear warhead employed in the Trident SLBM system
W80	thermonuclear warhead employed in U.S. Air Force and Navy cruise missiles
W88	thermonuclear warhead employed in the Trident SLBM system
Z accelerator	a pulsed-power facility at SNL, sometimes referred to as Z
Z	unit of atomic charge

K

NNSA
National Nuclear Security Administration