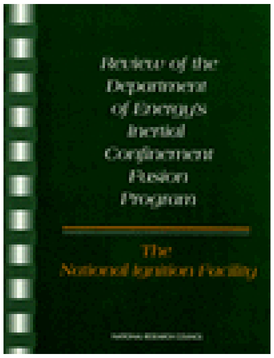

Review of the Department of Energy's Inertial Confinement Fusion Program: The National Ignition Facility

Committee for the Review of the Department of Energy's Inertial Confinement Fusion Program, National Research Council

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THE NATIONAL ACADEMIES
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Review of the Department of Energy's Inertial Confinement Fusion Program

The National Ignition Facility

Committee for the Review of the Department of Energy's Inertial Confinement Fusion Program
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

NATIONAL ACADEMY PRESS
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This report was not prepared in compliance with the Federal Advisory Committee Act (FACA), 5 U.S.C. App. 2, as determined by the United States District Court for the District of Columbia on March 5, 1997. The Committee that assisted the National Research Council in preparing this report has since been disbanded. The Department of Energy (DOE) was temporarily enjoined from using the report, but that injunction has been lifted, effective March 8, 2000, and thus all use of the report by DOE is now permitted.

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Preface

The Committee for the Review of the Department of Energy's Inertial Confinement Fusion Program was formed in response to a request from the Department of Energy's (DOE's) Assistant Secretary for Defense Programs, Victor H. Reis, that the National Research Council (NRC) review the DOE's Inertial Confinement Fusion (ICF) program. The recent declaration of Science Based Stockpile Stewardship (SBSS) as national policy within the broader Stockpile Stewardship and Management Program implies changes in the nuclear weapons program and resulted in a DOE decision that the ICF program, a component of SBSS, should undergo regular evaluation to ensure its continuing quality and its capacity to contribute both to SBSS and to other national needs.

The committee (brief biographies are given in Appendix C) includes members with expertise in theoretical and experimental plasma physics, theoretical and applied hydrodynamics and fluid dynamics, high-energy physics, nuclear physics, laser physics, optics and optical engineering, laser-plasma interactions, and computing and computer science. In addition, the membership includes individuals experienced in designing, building, and managing large experimental facilities. One member has experience in nuclear weapons design, and another is a long-time leader of a nongovernmental organization concerned with national nuclear energy and weapons policy. All committee members are recognized as leaders in their respective fields of expertise. Several have served on previous committees that have examined ICF, and several have consulted for Lawrence Livermore National Laboratory in various areas. Slightly less than half of the members have had no prior exposure to ICF and the NIF. Only a few have had prior exposure to weapons physics and weapons design. As a result, the present report expresses, to a large extent, the views of a group of experts outside the nuclear weapons establishment.

The charge to the committee was as follows:

> Conduct an initial review to: (1) determine the scientific and technological readiness of the NIF project, (2) assess the entire ICF program (including program scope, balance, and priorities; facility operation; experimentation; theory; etc.) and make recommendations to facilitate the achievement of the scientific goal, which is ignition, and (3) evaluate the capabilities of the ICF program (in conjunction with NIF) to support SBSS.

This charge to the committee does not request reassessment of the desirability of the Comprehensive Test Ban Treaty, the necessity for SBSS, or the nonproliferation aspects of ICF. Nor does it ask for recommendations about whether or not to construct the proposed NIF, a decision that involves considerations beyond the scientific and technical issues considered here.

To address its charge, the committee met five times to receive briefings, visit ICF facilities, and deliberate. Meetings were held at the Beckman Center in Irvine, California, Lawrence Livermore National Laboratory, the University of Rochester Laboratory for Laser Energetics, Los Alamos National Laboratory, Sandia National Laboratories, and at NRC facilities in Washington, D.C. Detailed meeting agendas and lists of attendees are provided in Appendix A. The committee also convened on December 17–18, 1996, at the California Institute of Technology to complete its report. In addition to these meetings, several members met independently with ICF program managers and scientists to obtain more detailed information. Other members gathered information by telephone, private correspondence, and electronic mail or submitted written requests for specific information to ICF managers and scientists.

The work of this committee follows that of prior review groups. The NRC previously has reviewed the ICF program twice, in 1986 under William Happer of Princeton University as chair and in

1990 under the current committee's chair, Steven Koonin of the California Institute of Technology. An internal DOE advisory committee, the Inertial Confinement Fusion Advisory Committee (ICFAC), met periodically from late 1992 to late 1995 to review selected aspects of the program as directed by the DOE's assistant secretary for defense programs. ICFAC held a total of seven meetings to examine technical issues such as time-dependent hohlraum asymmetries, the progress of the light ion program, the importance of the KrF laser program, contributions of the OMEGA program, and progress and issues in target physics, cryogenic targets, and target fabrication.

This is the first report of the present committee. Given the time available to it and the unfamiliarity of some committee members with ICF and/or nuclear weapons, the committee has not been able to obtain a thorough overview of the entire ICF program. As a result, the committee decided, with the concurrence of DOE, to address in this report only part of its charge: item 1 (the scientific and technological readiness of the NIF) and those portions of item 3 (the relevance of ICF to SBSS) that are directly connected to the NIF project. Thus, the report does not consider such topics as the appropriate balance of efforts between the several thrusts of the ICF program. The committee hopes to provide substantial responses to the rest of its charge in subsequent reports, after a more extensive exposure to the ICF program.

Contents

Executive Summary

BACKGROUND[1]

During the Cold War years, one of the Department of Energy's (DOE's) principal priorities was the design, testing, and production of nuclear weapons, with ancillary responsibilities related to assuring the safety, reliability, and performance of the stockpile. Nuclear testing was the major tool used to verify new designs, to assess design or construction flaws, and to certify design and manufacturing changes made to correct those flaws. The end of U.S. nuclear testing brought a new challenge to the DOE: the need to ensure the safety, reliability, and performance of an aging inventory of nuclear weapons, and to maintain core intellectual and technical competencies in nuclear weapons without conducting nuclear tests.

It is stated national policy that this challenge will be met through Science Based Stockpile Stewardship (SBSS), part of the broader Stockpile Stewardship and Management Program. SBSS seeks to provide the fundamental technical understanding and capabilities required to manage a safe and reliable stockpile of nuclear weapons under the Comprehensive Test Ban Treaty. This task includes the development of increased technical understanding of weapons and weapons-related technologies, including the underlying science, to permit confident prediction, without nuclear testing, of the effects of aging on the safety and performance of stockpiled weapons. An array of existing and planned facilities permit laboratory-level experiments to study the equations of state, opacities, radiative transport, and hydrodynamics that are necessary, together with substantial increases in computational power, to develop improved computer simulation models of nuclear weapons. The proposed National Ignition Facility (NIF), part of the Inertial Confinement Fusion (ICF) program, is intended to develop plasma conditions that in many respects would be closer than those of any other facility to the plasma conditions of a nuclear weapon.

Part of the fundamental understanding required for SBSS is expected to come from the ICF program, whose primary scientific goal as stated by DOE is the release of significant fusion energy in the laboratory. Achieving this release of energy requires that a small mass of deuterium-tritium fuel be compressed and heated to "ignition,"[2] a condition in which the initial fusion energy produced will induce further fusion in the fuel before the mass disassembles. Experiments conducted thus far have proved the concept of ICF, but none of the current facilities is capable of creating the conditions necessary to drive a capsule of deuterium-tritium fuel to ignition. With the goal of achieving ignition, the DOE has proposed building a new, 192-beam Nd:glass laser system capable of routinely delivering 1.8 MJ of 350-nm light at a power of 500 TW. This National Ignition Facility, at a stated total project cost (TPC) of $1.148 billion, is expected to contribute to several DOE mission areas, the SBSS program being foremost among them.

RELEVANCE OF THE NATIONAL IGNITION FACILITY TO SCIENCE BASED STOCKPILESTEWARDSHIP

Ignition is relevant to SBSS, but the NIF would make contributions to SBSS independent of ignition: Its experimental program would help attract and train people in weapons-related skills, provide

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[1] See the preface for a discussion of the committee's charge and the scope of this report.

[2] The definition of "ignition" adopted here is fusion energy output greater than laser energy incident on the target assembly (for indirect drive, the target assembly consists of the hohlraum and capsule; for direct drive, it consists of the capsule); see the section titled "Definition of Ignition" in Chapter 1.

microphysics data, enable integrated code validation, and create hohlraum conditions unique in a laboratory setting (high radiation temperatures foremost among them).

One of the stated goals of the SBSS program is to maintain core intellectual and technical competencies in nuclear weapons in the absence of nuclear testing. This key aim of SBSS requires a challenging theoretical, computational, and experimental program in the areas of implosion hydrodynamics, instabilities and mix, radiation transport, and theormonuclear burn. In the committee's judgment, ICF provides a unique synthesis of these relevant physics areas, and the NIF would provide unique capabilities for basic experiments in atomic physics, radiation flows, plasma physics, and hydrodynamics. In the collective judgment of the committee, the NIF should stimulate the scientific imagination and attract excellent scientists and engineers more than any other proposed element of SBSS. This assertion is supported by the ICF program's history of attracting and retaining high-quality personnel. Indeed, the attraction of the NIF is so high that it may be a management and leadership challenge to keep the ICF program in proper balance with the rest of SBSS.

Prior to the start of the moratorium on nuclear testing, weapons designers could unambiguously confirm their judgments and refine their skills through the success or failure of their devices in underground tests. In the new era of a complete nuclear test ban, the NIF can provide weapons stewards with a similarly challenging alternative for refining and proving their skills. Predicting ICF results in well-diagnosed experiments and ultimately achieving ignition are in many respects more technically demanding than making a nuclear weapon work.

The NIF will provide unique experimental conditions in a controlled environment from which extensive and relevant data can be extracted for both ICF and SBSS applications. The decision to undertake a policy of SBSS implies moving in the direction of first-principles predictive capability in hydrodynamics and radiation transport. While other facilities are expected to provide similar data, the NIF will access different regimes of such parameters as temperature, density, and scale length. Current and former members of the weapons community are debating the extent to which the data to be gained on facilities such as the NIF are applicable to the stockpile. As SBSS is a venture into uncharted technical and organizational territory, this issue can only be resolved by experience. Although many real engineering issues would not be tested directly on facilities such as the NIF, a skilled practitioner could use NIF experiments to develop an understanding of the relevant physics and apply the judgment he develops to analyze stockpile problems as they arise.

SCIENTIFIC READINESS

The NOVA Technical Contract (NTC) of 1990[3] specifies seven experimental objectives in hohlraum laser physics (HLP 1 to 7) and five in hydrodynamic equivalent physics (HEP 1 to 5) that were to be completed in preparation for proceeding to construction of an ignition facility. Although the completion of the NTC cannot guarantee that ignition will be achieved with the NIF, the completion of each milestone, in the context of the understanding of the underlying physics gained in pursuing it, increases confidence in the extrapolation of the results to the performance of the NIF. DOE's assessment of the technical readiness to proceed to Critical Decision 2 (CD-2)[4] was based partly on sustained progress on the NTC and on the extrapolation of those results to the NIF. Since CD-2, the NIF baseline target design has been changed to a gas-filled hohlraum. This change introduced unexpected but seemingly reproducible beam bending and increased backscatter so that several of the HLP 1 to 6 milestones are no longer met and others are, at best, barely met. The cause of this unexpected behavior is thought to be understood, and experiments with one NOVA beam smoothed indicate that beam

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[3] National Research Council, *Review of the Department of Energy's Inertial Confinement Fusion Program: Final Report*, National Academy Press, Washington, D.C., September 1990. The NTC requirements are summarized in Table 1.

[4] Steps taken by the DOE toward construction and operation of the NIF are called Critical Decisions (formerly Key Decisions). Critical Decisions 1 and 2 (approval of mission need, and project approval) have already occurred. The remaining Critical Decisions are CD-3 (authorization for start of physical construction and procurement, scheduled for April 1997) and CD-4 (end of construction project, scheduled for September 2003).

smoothing will restore the performance to that specified in the NTC; experiments with all 10 beams smoothed are scheduled for completion in FY97. Four of the five NTC milestones in capsule physics (HEP 1 through 4 in Table 1) have been met and the fifth—the convergence ratio of a successful target in the NIF geometry—has reached a value of 10, which is short of the originally projected value of 20.

The HEP 5 implosion experiments and modeling comparisons, intended to demonstrate implosion subject to overall hydrodynamic mix and spatial-mode spectra of capsules similar to ignition target designs, have not been successfully completed. Analysis following the original definition of these milestones, including limited three-dimensional hydrodynamics calculations and experiments, shows that the HEP 5 milestone is unrealistic in that it is beyond the reach of the present NOVA configuration and other currently available facilities. This same analysis shows that the NIF environment is compatible with the high convergence required for ignition, although wall motion issues have not been completely resolved. Fully integrated two-dimensional radiation-hydrodynamics calculations have allayed concerns about time-dependent low-mode number asymmetries. Although the milestone itself has not been reached, understanding of the physics behind it has been advanced significantly. An experimental campaign toward meeting the HEP 5 requirement, involving reconfiguration of the NOVA and OMEGA lasers, is in progress and would increase confidence in reaching ignition with the NIF. However, in the committee's judgment the additional technical confidence that might be gained by completion of milestone HEP 5 is not sufficient to justify delaying the NIF program.

Like current weapons studies, the ICF program supplements and interprets experimental studies with large-scale numerical simulations. The current generation of computer codes is not adequate to perform first-principles three-dimensional integrated calculations of an ignition target. However, the predictions of models that have been developed are in good agreement with the data and are consistent with the objectives of the NIF. The DOE has created the Accelerated Strategic Computing Initiative (ASCI) program to enhance computational resources and to stimulate the development of new and/or improved numerical methods and computational physics, as well as new classes of computer codes, especially three-dimensional codes. Three new high-performance computers have already been contracted for, delivery is in progress, and each will be phased in over the next 2 years. While all of these computers exploit parallel processing, they have very different architectural features that will require attention in developing applications aimed at achieving high performance. Even with these ASCI machines, the demands of three-dimensional calculations will still be severe, and good physical models coupled with good algorithms and code implementations will be required. Advanced developments enabled by the ASCI program in algorithms, models, and codes will be essential to realizing a true three-dimensional simulation capability.

On balance, while the current understanding of the science of the imploding capsule does not guarantee that ignition can be achieved with the NIF, it does give reasonable expectation that ignition will be achieved.

TECHNOLOGICAL READINESS

NIF Laser Technology

The expected NIF laser peak performance is 2.2-MJ of 350-nm light at 600-TW peak power. (The baseline operation is set at 1.8 MJ and 500 TW.) The NIF is composed of 192 beamlines, arranged into four arrays. Each array is composed of 4 × 12 segments, each with an aperture of 40×40 cm^2. The NIF design was selected from two conceptual designs based on multipass architecture. An original 240-beamline design was deferred and the current design with 192 beamlines was selected as a compromise, based on a reasonable expectation of reaching ignition with the lower energy and power and associated cost trade-offs. The NIF baseline uses a laser architecture selected to meet the required performance levels at acceptable cost while respecting the limits imposed by laser fluence damage.

The NIF laser will operate with larger optics than any previous laser system. It is based on a new laser architecture that reduces the number of optical elements, reduces the volume of the laser, and enhances the laser control and operational capability through a design that allows repair of laser beamlines between shots. To test these advanced concepts, a single laser beamline (called the Beamlet) was constructed. The Beamlet has been operational since 1994 and has provided a test bed to gain confidence in the NIF laser architecture and design, operating at the fluence levels planned for the NIF laser.

The Beamlet laser has validated almost all aspects of the design of the NIF laser. The exceptions are the final focusing optics and the lower damage threshold of the rapidly grown potassium dihydrogen phosphate (KDP) crystals; there are adequate plans for dealing with these two remaining issues. As designed, the NIF laser will operate at a maximum fluence consistent with an optimization of both cost and reliability and projected performance. The NIF laser architecture allows beamline maintenance and repair without disruption of normal operations. The beam-smoothing experiments under way on NOVA have demonstrated that the technology exists to meet the NIF laser performance specifications.

Targets

A baseline target design is in place and was used to specify the necessary operating parameters for the NIF. Possibilities for new and better targets, which would increase the likelihood of ignition, are being explored with the aid of recent advances in computational capabilities and related experiments. New ideas are being proposed regularly, including "cocktail" walls, different shapes for hohlraums, and new materials for capsules. The possibility that new and better targets might be developed before actual NIF operation in 5 or more years should not be discounted. Hohlraum designs are expected to evolve and be tested to accommodate the anticipated extension to cryogenic target capsules. Cryogenic layers with adequate smoothness (1 μm) have been demonstrated, albeit in surrogate geometries. Work is in progress on the problems of delivery and in situ characterization of cryogenic targets.

Continuing experiments and simulations are expected to further define capsule fabrication specifications. Given the evolution of the scientific understanding of hydrodynamic instabilities and the coupling between drive uniformity and capsule fabrication specifications, continuing progress in this area will increase the likelihood of achieving ignition with the proposed NIF.

The NIF Project

The NIF project organization and its relationship to the Lawrence Livermore National Laboratory (LLNL) appear sound and acceptable, with the critical elements in place to optimize the chances for successful project implementation and completion. The project has support from DOE management, and the project manager has sufficient administrative autonomy to accomplish work in a timely, efficient manner, including $25 million in procurement authority. The project leadership also has a good relationship with both DOE Oakland and DOE headquarters.

Since CD-2, the cost of the NIF has increased by $125 million for additional scope (see the section titled "The National Ignition Facility Project" in Chapter 4) and by $29 million for site-specific costs. However, these changes have increased the TPC by only $74 million (to $1.148 billion), because most of the start-up costs have been moved to the LLNL-projected operating budget for NIF and NOVA operations. In addition, there are NIF-related non-TPC costs of $397 million in LLNL-projected operating funds in FY98-FY02.

REMAINING HURDLES

Several technical issues should be pursued in parallel with NIF construction. While none is sufficiently serious to constitute a "showstopper," continued attention to all of them will to help ensure the NIF's success and its contributions to SBSS.

- **Consistent physical understanding of NIF-relevant phenomena.** Efforts should continue to better understand the requirements for convergence and compression with a modified NOVA configuration (HEP 5), laser-plasma interactions and the resulting "spot motion," the effects of hohlraum wall motion and the physics of plasma instabilities in gas-filled hohlraums, and the prediction, control, and diagnostics of the x-ray drive in hohlraums. Experiments to be conducted include the following:

1. Complete the 10-beam smoothing and wall-motion experiments in gas-filled hohlraums on NOVA. Implementation of the full smoothing by spectral dispersion (SSD) and random phase plates (RPPs) on all 10 beams will demonstrate further understanding of the potential limiting effects of laser-plasma interactions. Demonstrated low levels of stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS), and the resulting acceptable radiation temperatures, are expected.
2. Conduct experiments on retarding wall motion with improved azimuthal symmetry and a wider range of plasma conditions to further investigate the NIF hohlraum design.
3. Vigorously pursue experiments to study the behavior of Rayleigh-Taylor and Richtmyer-Meskov hydrodynamic instabilities in converging geometries.

- **Need for and challenges of three-dimensional simulations.** Current three-dimensional computer codes are inadequate for integrated calculations of ignition; their improvement will contribute significantly to increasing the probability of ignition. These codes must be adapted to run on ASCI platforms. The development of new, less empirical three-dimensional models and algorithms is necessary, as is benchmarking of three-dimensional codes by ICF experiments and test data. This effort is further challenged by the different characteristics of the machines purchased under the ASCI program.
- **Cryogenic capsule technology.** Advances should be sought in assembly, fill, and surface smoothness. Continued development of handling and delivery systems is also important to ignition, as are methods of characterizing the fuel in optically opaque cells. Researchers should explore target-design alternatives, advance target design and fabrication technology, and pursue cryogenic target experiments on OMEGA.
- **Optics damage thresholds and cost.** While the current cost estimate contains funds to purchase slow-growth KDP crystals if necessary, the effect on schedules must be considered if the fast-growth crystals fail to meet damage threshold requirements.

FINDINGS AND CONCLUSIONS

The NIF Would Make Important Contributions Toward the Stated Long-Term Goals of the SBSS Program

The proposed NIF is a flexible, high-power, high-energy laser facility that will address fundamental high-energy-density physics issues while creating in the laboratory conditions approaching those relevant to a nuclear weapon. The challenge of achieving ignition should help attract and sustain a cadre of talented scientists and engineers with weapons-relevant experience and expertise. The challenge of *predicting* results of NIF experiments will provide a "certification" of future weapons stewards analogous to that provided by the underground test experience of the present designers. The NIF's experimental capabilities will complement other SBSS activities by allowing unique experiments probing weapons-related physics.

The Science and Technology Have Progressed Sufficiently to Allow the NIF Project to Proceed as Planned

In assessing the scientific and technical readiness of the proposed NIF project, the committee attempted to balance the NIF's potential value against the risk inherent in extrapolation from the present base of experimental and computational experience. The committee believes that the NIF can be delivered to specifications within the stated TPC, as augmented by LLNL-projected operating funds, allowing the high-energy-density and ignition experimental programs to proceed; there are no identifiable "show stoppers." The achievement of ignition appears likely, but not guaranteed. The steady scientific and technological progress in ICF during the 6 years since the last National Research Council review,[5] the plausibility of ignition estimates based on the experimental and modeling results and capabilities in hand, and the flexibility of the proposed facility all support the committee's finding that the NIF project is technologically and scientifically ready to proceed as planned with reasonable confidence in the attainment of its objectives.

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[5] National Research Council, *Review of the Department of Energy's Inertial Confinement Fusion Program: Final Report*, National Academy Press, Washington, D.C., September 1990.

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Background

The end of the Cold War in the early 1990s has brought fundamental and far-reaching changes to the Department of Energy's (DOE's) national security mission and to the National Laboratories that are the department's scientific arm. Among the important factors leading to these changes are a decline in defense spending, increasingly far-reaching arms-control treaties, and a growing fear of the proliferation of weapons of mass destruction.

During the Cold War years, one of DOE's principal priorities was the design, testing, and production of nuclear weapons, with ancillary responsibilities related to ensuring the safety, reliability, and performance of the stockpile. Nuclear testing was the major tool used to verify new designs, to assess design or construction flaws, and to certify design and manufacturing changes made to correct those flaws.

The end of U.S. nuclear testing brought a new challenge to the DOE: the stated national needs to ensure the safety, reliability, and performance of an aging inventory of nuclear weapons, and to maintain core intellectual and technical competencies in nuclear weapons without conducting nuclear tests. It is stated national policy that this challenge will be met through Science Based Stockpile Stewardship (SBSS), a program that seeks to provide the fundamental technical understanding and capabilities required to manage a safe and reliable stockpile of nuclear weapons under the Comprehensive Test Ban Treaty.

Briefly outlined below are the circumstances that have led to the U.S. nuclear test moratorium, the requirements imposed on the SBSS program, and a brief description of that program, particularly its Inertial Confinement Fusion (ICF) and National Ignition Facility (NIF) components.

THE COMPREHENSIVE TEST BAN

In July 1993, President Clinton announced that a safe, secure, and reliable U.S. nuclear deterrent will remain a cornerstone of U.S. national security policy. He further extended a moratorium on U.S. nuclear testing initiated under President Bush and stated his wish to establish a comprehensive test ban. To support these actions he directed both the Department of Defense (DOD) and the DOE to explore means to maintain confidence in the safety, reliability, and performance of the stockpile in the absence of nuclear tests. The FY94 National Defense Authorization Act (P.L. 103-160) 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 August 1995, President Clinton made an additional statement concerning the Comprehensive Test Ban Treaty:[1]

> One of my administration's highest priorities is to negotiate a Comprehensive Test Ban Treaty to reduce the danger posed by nuclear weapons proliferation. To advance that goal and secure the strongest possible treaty, I am announcing today my decision to seek a "zero" yield CTBT. . . .I consider the maintenance of a safe and reliable nuclear stockpile to be a supreme national interest of the United States. I am assured by the Secretary of Energy and the directors of our nuclear weapons labs that we can meet the challenge of maintaining our nuclear deterrent under a CTBT through a Science Based Stockpile Stewardship program [SBSS] without nuclear testing. . . .While I am optimistic that the stockpile stewardship program will be successful, as President I

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[1] Statement by the President: Comprehensive Test Ban Treaty, The White House, Office of the Press Secretary, August 11, 1995.

> cannot dismiss the possibility, however unlikely, that the program will fall short of its objectives. . . .In the event that I were informed by the Secretary of Defense and Secretary of Energy. . . that a high level of confidence in the safety or reliability of a nuclear weapons type which the two Secretaries consider to be critical to our nuclear deterrent could no longer be certified, I would be prepared, in consultation with Congress, to exercise our "supreme national interests" rights under the CTBT in order to conduct whatever testing might be required. . . .The nuclear weapons in the United States arsenal are safe and reliable, and I am determined our stockpile stewardship program will ensure they remain so in the absence of nuclear testing.

In September 1996, the United States and more than 90 nations signed the Comprehensive Test Ban Treaty. According to international law, the United States, by virtue of its signing of the treaty, is already enjoined from nuclear testing, although the treaty has not entered into full force.

SCIENCE BASED STOCKPILE STEWARDSHIP

There has long been a formal program[2] to assess the nuclear stockpile and to deal with problems of safety and reliability as they have arisen. This program has included destructive and nondestructive studies of the physical, dynamic, geometrical, mechanical, metallurgical, and chemical properties of weapons and their components; testing, both nuclear and nonnuclear, has played a central role, but only nonnuclear testing will continue under the Comprehensive Test Ban Treaty. This surveillance program has, in fact, uncovered problems in the U.S. stockpile, some of which have affected large numbers of devices and required significant resources to resolve. To date, the DOE has been able to address all such identified problems and to certify the safety and reliability of the existing stockpile. However, it is almost certain that other problems will arise and be identified as the current stockpile ages and as advancing analytical skills are brought to the surveillance program. Only very limited nuclear test data are available on weapons with long stockpile sojourns.

The SBSS program is one element of the Stockpile Stewardship Management Program designed to ensure that the no-testing regime remains robust into the future and that the United States will not have to invoke its "supreme national interests" option and resume nuclear testing. [3] Its central challenge is to maintain a continuing capability to anticipate, detect, and evaluate actual and potential problems related to aging in the enduring nuclear stockpile and to plan for refurbishment and remanufacture as required.[4] Meeting this challenge requires the development of increased technical understanding of weapons and weapons-related technologies, including the underlying science, to permit confident prediction, without nuclear testing, of the effects of aging on the safety and performance of weapons. This responsibility includes preserving the core intellectual and technical competencies of the DOE weapons laboratories. It involves enhanced surveillance of the stockpile and remediation of defects as they arise. SBSS entails improving the National Laboratories' experimental capabilities and enhancing their computational capabilities. The decision to undertake a policy of SBSS implies moving in the direction of first-principles predictive capability in hydrodynamics and radiation transport. The advanced stockpile surveillance and manufacturing and materials capabilities of the broader Stockpile Stewardship Management Program are also necessary, as are the maintenance of system engineering and infrastructure and the preservation of nuclear design and experimentation skills. [5]

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[2] K. Johnson, J. Keller, C. Ekdahl, R. Krajcik, L. Salazar, E. Kelly, and R. Paulsen, *Stockpile Surveillance: Past and Future*, Sandia Report SAND95-2751-UC-700, Sandia National Laboratories, Albuquerque, New Mexico, January 1996. See also Sidney Drell and Bob Peurifoy, "Technical Issues of a Nuclear Test Ban," *Annu. Rev. Nucl. Part*. 44:285–327, 1994.

[3] *The Stockpile Stewardship and Management Program: Maintaining Confidence in the Safety and Reliability of the Enduring U.S. Nuclear Weapon Stockpile*, U.S. Department of Energy, Office of Defense Programs, May 1995.

[4] *Nuclear Testing*, JASON report JSR-95-320, The MITRE Corp, McLean, Virginia, Aug. 1995.

[5] *Alternative Futures for the Department of Energy National Laboratories* , prepared by the Task Force on Alternative Futures for the Department of Energy National Laboratories, Department of Energy, Washington, D.C., February 1995.

The principal facilities of the SBSS program, as provided to the committee by DOE, are listed in Appendix B. This array of planned facilities and programs is designed to carry out above-ground experimentation (AGEX) relevant to weapons. These laboratory-level experiments permit studies of equations of state, opacities, radiative transport, and hydrodynamics that are necessary, together with substantial increases in computational power, to eventually construct predictive computer models of nuclear weapons. Previously, nuclear tests were a source of these data and the primary validation of such models. Several AGEX facilities create and explore confined plasmas at conditions close to, but not coincident with, those of a nuclear weapon. The proposed National Ignition Facility (NIF), part of the Inertial Confinement Fusion (ICF) program, is intended to develop plasma conditions that in many respects would be closer than those of any other facility to the conditions of a nuclear weapon, thereby reducing, but not eliminating, uncertainties in the extrapolation to the conditions in a nuclear weapon.

The National Laboratories must carry out the tasks of SBSS consistent with the broad nonproliferation goals of the United States. In this regard, others have assessed the NIF with the conclusion that the concerns about nonproliferation were manageable, that the risks could be made acceptable, and that the NIF could contribute positively to U.S. arms control and nonproliferation goals.[6]

INERTIAL CONFINEMENT FUSION

The physics of matter and radiation at high energy density and the physics of thermonuclear fusion are central issues for SBSS. One goal of the ICF program is to explore all of these elements in a laboratory setting. The following sections, included to make this report relatively self-contained, briefly describe the ICF program's goals and present facilities, as well as the NIF.

Scientific Goal

The DOE has stated that the primary scientific goal of the ICF program is the release of significant fusion energy in the laboratory. ICF requires that a small mass of deuterium-tritium fuel be rapidly compressed and heated to ignition, so that the initial fusion energy produced will induce further fusion in the fuel before the mass disassembles. In ICF, a spherical fuel capsule of a few millimeters in size is compressed by ablation of material from the capsule surface. Compression is achieved by either direct or indirect drive. In direct drive, laser or ion beams impinge directly on the capsule surface, causing ablation and compression. In "indirect drive, the capsule is placed in an enclosure (hohlraum) made of a high-Z (high atomic number) material such as gold. Laser energy is directed to the hohlraum's inner surface, where it is converted to x-rays; these x-rays impinge on the capsule and cause ablation. Relative to direct drive, indirect drive suffers the inefficiency of x-ray conversion, but it imposes less stringent requirements on beam balance and uniformity.

Current Facilities

The DOE's ICF program began formally in 1963 and was established as a separate budget line item in 1976. Several of the National Laboratories, universities, and commercial firms have participated in this program. Several major facilities are currently active in performing experiments relevant to both direct and indirect drive.

The NOVA laser facility at Lawrence Livermore National Laboratory is a 10-beam Nd:glass laser system that is being used to explore indirect drive. Each beam can deliver 8 to 10 kJ of 1050-nm light in variable pulse shapes to 5 ns; up to 40 kJ of frequency-tripled, 350-nm light can be delivered routinely. The OMEGA laser facility at the University of Rochester's Laboratory for Laser Energetics (LLE) is a 60-beam, 30-kJ, pulse-shaped, 350-nm glass laser system intended primarily to explore the direct drive option. The Naval Research Laboratory is also pursuing studies of direct drive with its NUCE KrF gas laser, which produces 4 to 5 kJ of 248-nm light in a 4-ns pulse. The Particle Beam Fusion

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[6] U.S. Department of Energy, Office of Arms Control and Nonproliferation, *The National Ignition facility (NIF) and the Issue of Nonproliferation,*Final Study, NN-40, Washington, D.C., December 19, 1995.

Accelerator Z at Sandia National Laboratories in Albuquerque, New Mexico, is a facility that uses pulsed power to create an imploding plasma that generates x-rays. This novel and promising technology has demonstrated more than 150-TW power and 1.8-MJ energy, albeit at significantly lower energy density than that envisioned for the NIF. In addition to these driver facilities, capsule fabrication development is ongoing at General Atomics and at Los Alamos National Laboratory.

The National Ignition Facility

Experiments conducted thus far have proved the concept of ICF, but none of the current facilities is capable of creating the conditions necessary to drive present capsule configurations to ignition. With the goal of achieving ignition, the DOE has proposed building a new, 192-beam Nd:glass laser system capable of routinely delivering 1.8 MJ of 350-nm light at a power of 500 TW. This National Ignition Facility, at a stated TPC of $1.148 billion,[7] is expected to contribute to several DOE mission areas. Beyond the primary SBSS role discussed in this report, the NIF has relevance to fusion energy: even though a flash-lamp-pumped glass laser is too inefficient to be the driver in a prospective inertial fusion energy plant, achievement of ignition with the NIF would help establish design requirements for commercially relevant drivers and other components of an eventual inertial confinement fusion power plant. The NIF is also expected to contribute to basic science and to attract scientists worldwide through its unique ability to provide experimental conditions relevant to atomic, nuclear, and stellar physics, supernova explosions, and cosmology.

DEFINITION OF IGNITION

The definition of ignition, while seeming straightforward at first glance, is not necessarily a point of consensus within the community of ICF researchers. Therefore, the committee has adopted an operative definition for the purposes of this report.

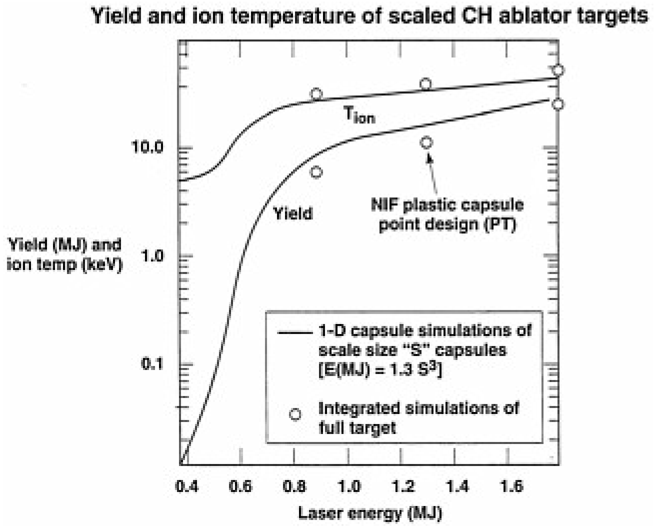

Figure 1 Predicted nominal energy output as a function of energy incident on the National Ignition Facility point design target. Source: Lawrence Livermore National Laboratory.

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[7] David C. Rardin, *Title I Cost Estimate*, presented at the NIF Fourth Quarterly Review, DOE, Germantown, Maryland, November 7, 1996.

Figure 1 shows the predicted nominal fusion energy output as a function of the laser energy incident on the NIF point design target presented to the committee. It indicates that the predicted gain (ratio of fusion yield to laser energy) at the nominal laser energy is about 6. The shape of the yield curve is cliff-like, in that fusion yield increases very rapidly, from near zero to its full value, over a relatively small range of incident laser energy. A plot of fusion yield as a function of other relevant drive parameters (such as laseruniformity or capsule surface finish) would exhibit a similar structure. This curve leads to the operative definition of ignition adopted by the committee: *gain greater than unity*.

However, there are two diagnosable milestones on the yield curve. At a gain of about 0.1, energy deposited by fusion alpha particles is sufficient to double the central temperature. At a gain of about 0.3, fusion reactions occur over a sufficient region to induce propagation of the thermonuclear burn into the denser, colder, outer fuel.

2

Relevance of the National Ignition Facility to Science Based Stockpile Stewardship

Ignition is relevant to SBSS, but the NIF will make contributions to SBSS independent of ignition: Its experimental program will help attract and train people in weapons-related skills, provide microphysics data, enhance integrated code validation, and create hohlraum conditions unique in a laboratory setting (high radiation temperatures foremost among them).

PEOPLE

One of the stated goals of the SBSS program is to maintain core intellectual and technical competencies in nuclear weapons in the absence of nuclear testing. Previous reviews[1] have recognized that a successful SBSS program requires the ability to sustain and enhance the scientific competence of the National Laboratories. In particular, the National Laboratories must be able to attract, train, and retain competent and creative scientists with the skills necessary to understand nuclear weapons and to certify the stockpile. Appropriate personnel are best attracted and retained by the opportunity to participate in challenging basic research. The maintenance and renewal of technical skills and overall scientific competence can be best fostered through ambitious technical challenges and the opportunity for scientific recognition, both through publication in the open literature and through performance in the classified community. These conditions are important to ensuring an imaginative and high-quality SBSS program. The committee believes that a stewardship program based only on the static knowledge and technology of the past would find it difficult to attract and maintain the necessary scientific talent. The stewardship community must be able to respond to unforeseen challenges, including technical issues in support of treaty negotiations, as well as the recognized issues of safety, security, reliability, aging, remanufacturing, and proliferation monitoring and control.

Maintaining core intellectual and technical competencies requires a challenging theoretical, computational, and experimental program in the areas of implosion hydrodynamics, instabilities and mix, radiation transport, and theormonuclear burn. In the committee's judgment, ICF provides a unique synthesis of these relevant physics areas, and the NIF would provide unique capabilities for basic experiments in atomic physics, radiation flows, plasma physics, and hydrodynamics. In the collective judgment of the committee, the NIF should stimulate the scientific imagination and attract excellent scientists and engineers more than any other proposed element of SBSS. This assertion is supported by the ICF program's history of attracting and retaining high-quality personnel. While it is difficult to quantify how much more successful the NIF would be in attracting personnel than other proposed SBSS facilities, a majority of the committee members are involved in the training of scientists, and their consensus is that they would more strongly encourage their students to work on the NIF than on any other proposed SBSS facility. The attraction of the NIF is so high that, indeed, it may be a management and leadership challenge to keep the ICF program in proper balance with the rest of SBSS.

Universities are the primary source of scientific and technical talent, and the NIEF will provide new opportunities for university-National Laboratory synergism, both in personnel and in science. Beyond the long-standing LLE effort at the University of Rochester, universities have been involved in the ICF program at a modest but increasing rate since recent declassification of much of the program. For example, a new program makes about 10% of the NOVA shots available, at no charge, to university experts in laser-matter interactions and high-energy-density physics, on the basis of brief proposals focused on basic science. Other ICF facilities have similar outreach programs; more than 100 graduate

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[1] *Science Based Stockpile Stewardship*, JASON report, JSR-94-345, the MITRE Corp., McLean, Virginia, November 1994.

students and some $5 million in funding are involved. These opportunities can be exploited most effectively by moving from the present National Laboratory-driven university grant program to the very successful user models in nuclear physics, high-energy physics, and basic energy sciences. Here, large facilities are regarded as tools available to both university and National Laboratory scientists for collaborative pursuit of shared scientific goals. Furthermore, university participants have typically been supported by funding independent of the National Laboratories, usually from either the DOE Office of Energy Research or the National Science Foundation.

CERTIFICATION OF WEAPONS STEWARDS

Predicting ICF results in well-diagnosed experiments and ultimately achieving ignition are in many respects more technically demanding than making a nuclear weapon work. Significant surprises in NIF results might be an objective signal of inadequacies in the SBSS program and would spur efforts to improve basic understanding of weapons physics.

Prior to the start of the moratorium on nuclear testing, weapons designers could unambiguously confirm judgment and refine their skills through the success or failure of their devices in underground tests. In the new era of a complete nuclear test ban, the NIF can provide weapons stewards with a similarly challenging alternative for refining and proving their skills. Hydrodynamic motion, radiation flow in diverse geometries, and ultimately capsule ignition and burn would be examined in great detail in NIF experiments. The ability to do "pre-shot" modeling of these phenomena will be a significant certification of weapons stewards' skills and a continuing challenge for those skills.

CODE VALIDATION AND MATERIALS PROPERTIES

Several relatively new experimental programs exploit lasers and pulsed power to collect data and validate the weapons physics in codes relevant to SBSS. These efforts are aimed at understanding genuinely three-dimensional systems and measuring opacities, equations of state, the dynamic response of materials, hydrodynamics, and radiative transfer. These studies do not have sharp requirements in laser energy or performance; indeed, they have been carried out at NOVA, as well as at the LANL Trident laser facility, NRL's NIKE laser facility, and LLE's OMEGA. However, the NIEF would carry these studies into new and more relevant domains.

It is expected that the NIF would provide a controlled environment from which extensive and novel data can be extracted for both ICF and SBSS applications. Such data are critical for the validation of the design codes that are applied to ICF targets and are relevant to the prediction, evaluation, and analysis of weapons physics issues. While other facilities are expected to provide similar data, the NIF would access different regimes of such parameters as temperature, density, and scale length. This full suite of data is required to attempt to meet SBSS objectives under the Comprehensive Test Ban Treaty.

The complex physics involved in ICF and SBSS studies implies a corresponding complexity in the radiation-hydrodynamics codes used; these codes push the state of the art in many ways, including differencing methods, parallel computation techniques, and physics modules. Even in the absence of ignition, the NIF has key roles to play in the maturation, maintenance, and advanced development of these codes, which have a use in other DOE technical and scientific programs.

In addition to providing data for critical, yet standardized, tests of codes (including grid resolution and convergence studies), the NIF environment would allow some of the physics models involved to be developed, tested, and evaluated. Since a first-principles formulation of such models is generally not possible at this time, the phenomenology used must be calibrated against an extensive and reliable database spanning the range of expected conditions. The NIF may be the best tool to provide this calibration for many of the models of interest.

For example, ions with high atomic number have a complex set of electronic configurations and ionization states whose descriptions strain both computational and experimental techniques. A benchmark class of experiments with the NIF will both calibrate and validate advanced computer codes that can be used to extend opacity tables and equation-of-state formulae into regimes important to both

ICF and SBSS. Current computer codes have limited capabilities to treat fully relativistic ionization and impact cross sections and reaction rates that are required to create reliable stand-alone simulation tools for design, analysis, and evaluation.

Much of the empiricism in weapons understanding and analysis is related to the fundamental issues of material mix and hydrodynamic instabilities. These issues can be addressed through experiments with the NEF, which would allow the detailed study of instabilities of many materials at densities and temperatures relevant to the stockpile. Experiments that simulate specific weapons-relevant geometries would be of particular interest.

Current and former members of the weapons community are debating the extent to which the data to be gained on facilities such as the NIF are applicable to the stockpile. As SBSS is a venture into uncharted technical and organizational territory, this issue can only be resolved by experience. Although many real engineering issues would not be tested directly on facilities such as the NIF, a skilled practitioner could use NIF experiments to develop an understanding of the relevant physics and apply the judgment he develops to analyze stockpile problems as they arise.

IGNITION

In terrestrial environments to date, significant thermonuclear burn in a dense plasma occurs only in weapons. Achieving ignition on the NIF would thus open a new realm of physical study relevant to weapons science, to basic research, and to energy production. Among the possibilities are the following:

- *The study of burn in the presence of mix*. The physics of thermonuclear bum in the presence of mixed materials is central to nuclear weapons and to the consequences of defects and aging.
- *The diagnosis of ICF plasmas*. Because of the sensitivity of burn to various plasma conditions (temperature, density, geometries, impurities, and others), the detection of burn products will be a novel diagnostic of ICF plasmas. For example, diagnosing highly compressed, somewhat asymmetric, and partly-mixed targets is very difficult. The copious fusion products, which can be used for imaging and spectral analyses, should provide the best diagnostic for implosion quality.
- *High-energy-density-phenomena*. Ignition with the NIF would enable a closer approach to the energy densities of weapons (and some astrophysical situations) than that possible at any other laboratory facility; an x-ray spectrum desired for weapons effects studies would also be produced. In progressing from NOVA to the NIF to ignition with the NIF, each step represents approximately a one-order-of-magnitude increase in x-ray yield. Ignition on the NIF would create laboratory environments at multi-keV temperatures.
- *Proof-of-principle for inertial fusion energy (IFE)*. Much of the target physics for initial fusion energy (the use of ICF for commercial-scale power production) is driver independent. The NIF would enable study of the relative merits of direct and indirect drive, as well as a range of target designs. These studies will help to quantify the beam energy and beam quality requirements for ignition and for future reactor designs.

3

Scientific Readiness

BACKGROUND

The two major scientific uncertainties "in predicting ignition with the NIF are the laser-plasma interactions in the hohlraum and the hydrodynamic instabilities in the imploding capsule. The former reduce the uniformity and energy of the drive, while the latter limit the ultimate compression of the fuel that can be achieved.

The NOVA Technical Contract (NTC) of 1990 specifies seven experimental objectives in hohlraurn laser physics (HLP 1 to 7) and five in hydrodynamic equivalent physics (HEP 1 to 5) that were to be completed in preparation for proceeding to an ignition facility. Each NTC milestone was defined, and is limited by, the performance of the NOVA laser. Although the completion of the NTC cannot guarantee that ignition will be achieved with the NIF, the completion of each milestone, in the context of the understanding of the underlying physics gained in pursuing it, increases confidence in the extrapolation of the results to the performance of the NIF. DOE's assessment of the technical readiness to proceed to Critical Decision 2 (CD-2)[1] was based partly on sustained progress on the NTC and on the extrapolation of those results to the NIF.

The Target Physics Subcommittee of the ICFAC completed a detailed review of progress toward completion of the NTC on January 3, 1994, and endorsed proceeding to CD-2 of the NIF. The status of the NTC milestones at the completion of CD-2 is summarized in Table 1. Inspection of the differences between the NIF requirement and the NTC requirement for each category shows the degree of extrapolation necessary for reaching ignition on the NIF. Comparison of the NTC requirement and the value achieved at CD-2 in June 1994 shows that the milestones HEP 1, 2, 3, and 4 and HLP 1, 2, 6, and 7 were met to the satisfaction of the ICFAC subcommittee. There was also substantial progress in meeting HLP 4 and 5.

RESULTS SINCE CRITICAL DECISION 2

Four of the five NTC milestones in capsule physics (HEP 1 through 4 in Table 1) have been met and the fifth—the convergence ratio of a successful target in the NIF geometry—has reached a value of 10, which is short of the originally projected value of 20. However, in a different NOVA experiment, capsules in a different hohlraum geometry have achieved a convergence ratio of 24, suggesting that milestone HEP 5 would have been met if the laser symmetry on NOVA had been adequate.

The difference between the performance achieved and the performance expected in the NIF-like geometry deserves some examination. The original projections were based on two-dimensional calculations, which necessarily ignore the azimuthal asymmetry caused by the small number of beams on NOVA. More recent three-dimensional calculations are consistent with the observed convergence ratio of 10 on NOVA and the expected achievable value of 35 on the NIF. Fully integrated two-dimensional radiation-hydrodynamics calculations have addressed concerns about time-dependent low-mode number asymmetries. Although milestone HEP 5 itself has not been reached, understanding of the physics behind it has been advanced significantly. An experimental campaign toward meeting the HEP 5 milestone, involving reconfigured NOVA and OMEGA lasers, is in progress and would increase confidence in reaching ignition with the NIF. In the committee's judgment the additional technical

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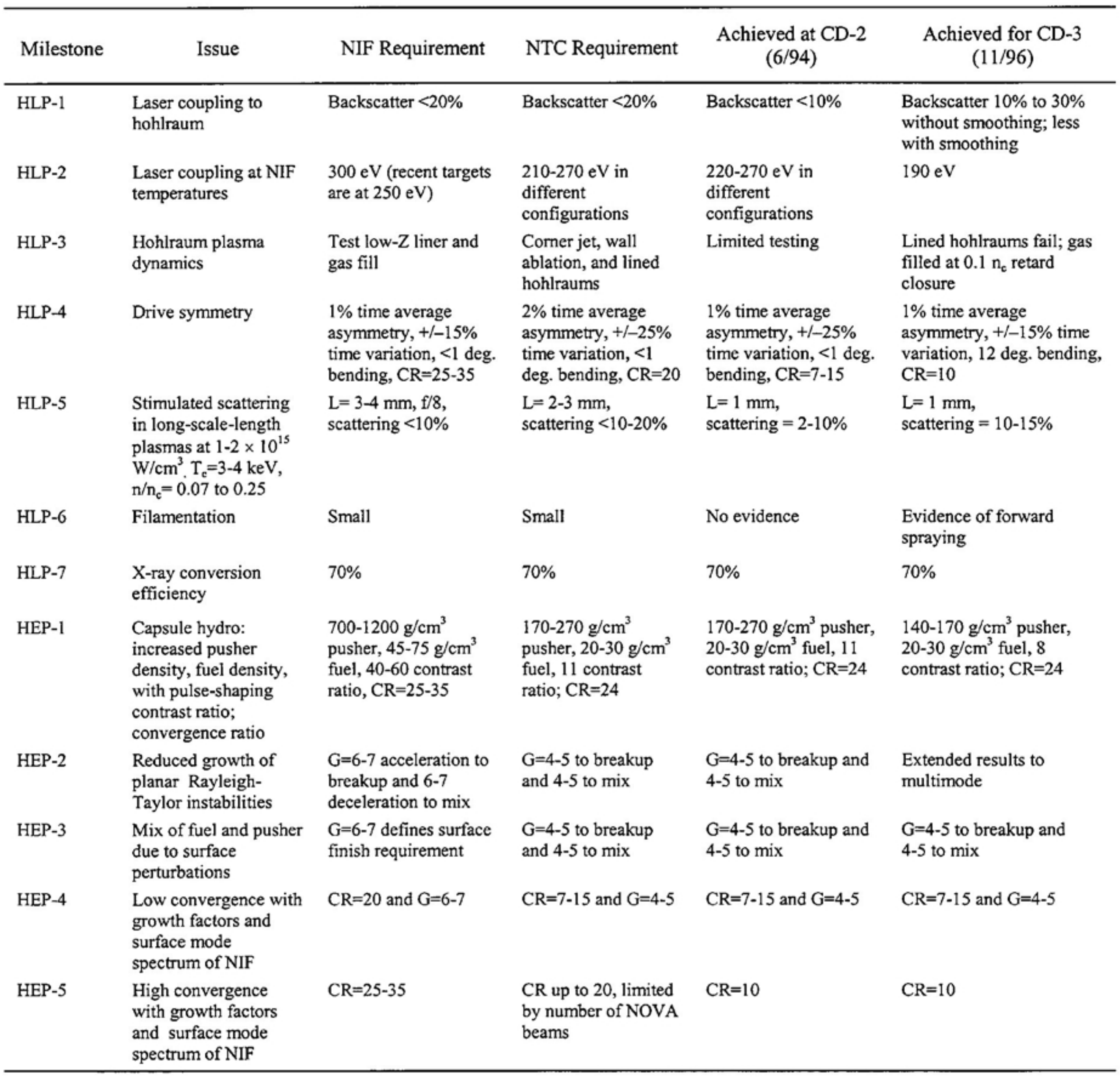
[1] Steps taken by the DOE toward construction and operation of the NIF are called Critical Decisions (formerly Key Decisions). Critical Decisions 1 and 2 (approval of mission need, and project approval) have already occurred. The remaining Critical Decisions are CD-3 (authorization for start of physical construction and procurement, scheduled for April 1997) and CD-4 (end of construction project, scheduled for September 2003).

confidence that might be gained by completion of this milestone is not sufficient to justify delaying the NIF program.

TABLE 1 Status of the NOVA Technical Contract



Milestone	Issue	NIF Requirement	NTC Requirement	Achieved at CD-2 (6/94)	Achieved for CD-3 (11/96)
HLP-1	Laser coupling to hohlraum	Backscatter <20%	Backscatter <20%	Backscatter <10%	Backscatter 10% to 30% without smoothing; less with smoothing
HLP-2	Laser coupling at NIF temperatures	300 eV (recent targets are at 250 eV)	210-270 eV in different configurations	220-270 eV in different configurations	190 eV
HLP-3	Hohlraum plasma dynamics	Test low-Z liner and gas fill	Corner jet, wall ablation, and lined hohlraums	Limited testing	Lined hohlraums fail; gas filled at 0.1 n_c retard closure
HLP-4	Drive symmetry	1% time average asymmetry, +/–15% time variation, <1 deg. bending, CR=25-35	2% time average asymmetry, +/–25% time variation, <1 deg. bending, CR=20	1% time average asymmetry, +/–25% time variation, <1 deg. bending, CR=7-15	1% time average asymmetry, +/–15% time variation, 12 deg. bending, CR=10
HLP-5	Stimulated scattering in long-scale-length plasmas at 1-2 × 10^{15} W/cm^3, T_e=3-4 keV, n/n_c= 0.07 to 0.25	L= 3-4 mm, f/8, scattering <10%	L= 2-3 mm, scattering <10-20%	L= 1 mm, scattering = 2-10%	L= 1 mm, scattering = 10-15%
HLP-6	Filamentation	Small	Small	No evidence	Evidence of forward spraying
HLP-7	X-ray conversion efficiency	70%	70%	70%	70%
HEP-1	Capsule hydro: increased pusher density, fuel density, with pulse-shaping contrast ratio; convergence ratio	700-1200 g/cm^3 pusher, 45-75 g/cm^3 fuel, 40-60 contrast ratio, CR=25-35	170-270 g/cm^3 pusher, 20-30 g/cm^3 fuel, 11 contrast ratio; CR=24	170-270 g/cm^3 pusher, 20-30 g/cm^3 fuel, 11 contrast ratio; CR=24	140-170 g/cm^3 pusher, 20-30 g/cm^3 fuel, 8 contrast ratio; CR=24
HEP-2	Reduced growth of planar Rayleigh-Taylor instabilities	G=6-7 acceleration to breakup and 6-7 deceleration to mix	G=4-5 to breakup and 4-5 to mix	G=4-5 to breakup and 4-5 to mix	Extended results to multimode
HEP-3	Mix of fuel and pusher due to surface perturbations	G=6-7 defines surface finish requirement	G=4-5 to breakup and 4-5 to mix	G=4-5 to breakup and 4-5 to mix	G=4-5 to breakup and 4-5 to mix
HEP-4	Low convergence with growth factors and surface mode spectrum of NIF	CR=20 and G=6-7	CR=7-15 and G=4-5	CR=7-15 and G=4-5	CR=7-15 and G=4-5
HEP-5	High convergence with growth factors and surface mode spectrum of NIF	CR=25-35	CR up to 20, limited by number of NOVA beams	CR=10	CR=10

NOTE: CR = convergence ratio; G = e-foldings of growth; L = plasma scale length, n_c = electron density at which laser light will no longer propagate.

Motion of the hohlraum wall during the laser pulse can impair the symmetry of the radiation on the capsule and spoil the implosion. Motion of the laser spots and the small number of beams on NOVA allowed three-dimensional effects to complicate the results of experiments addressing this issue. Considering all the experimental parameters, the data that are available on that phenomenon are consistent with the NIF design but are not adequate to resolve the wall-motion issue on the NIF.

The current generation of computer codes is not adequate to perform three-dimensional integrated calculations of the physics of the imploding capsule from first principles. However, the models that have been developed are in good agreement with the data and are consistent with the objectives of the NIF. Moreover, ICF target physics is sufficiently relevant to weapon physics to justify including the resolution of target-physics issues as worthwhile objectives for the operational phase of the NIF. On balance, while the current understanding of the science of the imploding capsule does not guarantee that ignition can be achieved with the NIF, it does gives reasonable expectation that ignition will be achieved.

Since completion of CD-2, progress has occurred in hohlraum laser-plasma physics. Prior to CD-2, most experiments utilized unlined gold hohlraums, with the short laser pulse on NOVA preventing significant wall motion from perturbing the capsule implosion. The long scale-length plasmas of the NIF hohlraum. were simulated by a gas bag. The data for the HLP milestones established as requirements for CD-2 were based on these two configurations. In addition, a NIF hohlraum. with a CH liner was proposed to retard wall motion on the longer time scales required on the NIF. Integrated modeling of the hohlraum and capsule and experiments showed that the plasma from the CH liner would stagnate on the axis and destroy the symmetry of the implosion. This realization led to the adoption of a gas-filled hohlraum as the baseline design. Elegant and detailed experiments with these gas-filled targets revealed lower temperatures, larger backscatter, evidence of filamentation, and larger beam bending than had been observed in the unlined hohlraums and gas bags. As shown in Table 1, the new experiments reduced the values achieved for the HLP 1, 2, 4, 5, and 6 milestones (in most respects, below the NTC requirements) but enhanced the understanding of the underlying physics and made the results more relevant to the NIF design.

Gas-filled hohlraums have shown two problematic effects: (1) a temporally dependent shift from the calculated symmetry of irradiation, equivalent to a beam position shift, and (2) a difference between measurements and modeling predictions (most importantly in radiation drive temperature). With respect to (1), the effect is qualitatively understood and is consistent with the high transverse flow velocity of the hohlraum plasma near the laser entrance hole. The shift can be compensated by optics on the NIF and/or by laser beam smoothing using random phase plates (RPPs) to suppress nonlinear filamentation (small-scale self-focusing) in the gas.

With respect to (2), propagation of the laser light through relatively long, subcritical-density plasmas in the hohlraum. results in loss of laser energy backscattered through stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The dynamics of these instabilities, and the resulting smaller wall radiation temperature in the gas-filled hohlraum, are understood qualitatively, but their saturation behavior is currently under intensive experimental and theoretical study. Again, the use of RPPs on one beam of NOVA has largely eliminated hot-spot-induced effects. An experimental solution to reducing total SBS and SRS backscatter was the introduction of smoothing by spectral dispersion (SSD) to broaden the laser bandwidth, in combination with an RPP. The result was 9% total measured backscatter with 0.05-nm SSD at the required laser intensity of 2×10^{15} W/cm^2,the intensity required for the 300-eV NIF target design temperature. This bandwidth for SSD is within the NIF baseline plan. Evaluation of consistency with the LASNEX two-dimensional modeling code awaits experiments following the implementation (in FY97) of 10-beam smoothing on NOVA.

MODELING CAPABILITIES

Current computer codes play key roles in target design, laser design, the modeling of laser-target interactions, the interpretation of experiments, and other ICF-related research projects. Codes in wide use today include one-and two-dimensional codes based on Lagrangian, Eulerian, mixed Eulerian-Lagrangian, and particle methods. For example, the LASNEX code is used in various forms at LLNL and LANL for a broad variety of ICF applications.

ICF target design models are routinely performed in one dimension, where the maximum range of physical processes can be modeled and parameter studies can be carried out economically.

Applications include the replication of implosion experiments, often on a shot-by-shot basis. A limited number of the most promising designs and representative experimental shots are simulated in two dimensions to assess the departure from the expected one-dimensional behavior.

Other codes are used to model the target corona, where temperature and density profiles must be calculated with high precision. Additional applications involve such problems as the effects of non-Spitzer thermal transport on thermal smoothing and cell focusing in the corona, as well as preheating in the ablation region.

The following kinds of physics are now reasonably well treated in one-and two-dimensional simulations:

- One fluid, two-temperature descriptions for electrons and ions;
- Thermal conductivity: electron and ion with flux-limited diffusion;
- Radiation transport: multigroup flux-limited diffusion using opacity tables based on local thermal equilibrium and an appropriate method of transport calculation;
- Complex equations of state;
- Laser deposition: inverse bremsstrahlung;
- Suprathermal electron transport: multigroup flux-limited diffusion effects;
- Thermonuclear burn and transport of reaction products: multigroup flux-limited diffusion; and
- Models of early-stage mixing, driven by hydrodynamic instability.

Other computer codes are routinely used now to model propagation of laser beams through the system and to compute critical properties such as opacities and other aspects of complex ICF-related physics.

Despite the significant simulation capabilities now available, the ICF program would benefit from improved, more comprehensive simulations of ignition and burn. The DOE has created the Accelerated Strategic Computing Initiative (ASCI) to enhance computational resources and to stimulate the development of new and/or improved numerical methods and computational physics, as well as new classes of computer codes, especially three-dimensional codes. Three new machines have already been contracted for, delivery is in process, and the machines will be phased in over the next 2 years. While all of these computers exploit parallel processing, they have very different architectural features that will require attention in developing applications aimed at achieving high performance. The three machines are described in Table 2.

Table 2 ASCI Computing Facilities

Machine	Location	Initial Configuration	Technology Refresh	Sustained Configuration
Red	SNL	4/97 (1800/600)	—	—
Blue Pacific	LLNL	10/96 (136/98)	1/97–4/97 (585/196)	1998 (3270/2500)
Blue Mountain	LANL	1/97 (102/128)	12/97 (422/256)	12/98–2/99 (3100/1500)

NOTE: Performance numbers are given as theoretical peak Gflops/s per gigabyte of memory.

Even with these ASCI machines, the demands of three-dimensional calculations will still be severe, and good physical models coupled with good algorithms and code implementations will be required. Advanced developments enabled by the overall ASCI program in algorithms, models, and codes will be essential to realizing a true three-dimensional simulation capability.

The basis of the correctness of these codes and, ultimately, the determining factor in the confidence with which they can be used, is the validity not only of the algorithms but also of the physics data sets and models used to calibrate and validate the codes. Some of these data sets are used internally in the codes to provide opacities, nuclear and atomic reaction rates, and equations of state, while others are used to compare computational with experimental data. The level of detail at which such experimental data can be used is clearly greater when the codes are three dimensional than when they are two or one dimensional. That is, comparison between experiment and computation in one dimension and two dimensions necessarily involves "coarse-graining" of data at a level that is not required in three dimensions. Obtaining useful data for three-dimensional modeling requires better diagnostic instrumentation and, in general, more advanced experimental facilities than are required for comparison with one-and two-dimensional code results. The NIF, with its advanced instrumentation and diagnostic facilities, is required to provide the inputs to yield real progress on three-dimensional computations. It is essential that future simulation capabilities be up to the task.

CONFIDENCE IN ACHIEVING THE SCIENTIFIC OBJECTIVES

The committee has considered two approaches to assessing the likelihood of achieving the scientific objectives of ignition and propagating burn on the NIF.

The first approach takes a historical perspective, looking at technical progress since the 1990 NRC review of the ICF program.[2] In the ensuing years of intense scrutiny of the NTC and the technical objectives that have evolved, the primary change to the laser functional requirements has been the addition of improved beam-smoothing techniques. Although the NTC anticipated the need for beam smoothing, the choice of smoothing technique awaited the results of laser-plasma interaction experiments. The main change in the baseline target design has been to replace a low-Z lined hohlraum with a gas-filled hohlraum. The lined hohlraum design was initially adopted because of its perceived greater ease of fabrication.

Although the change from a lined to a gas-filled hohlraum design had a minimal impact on the laser functional requirements, the program has nevertheless faced significant challenges during the past 6 years. To cite some specific examples: (1) the lined hohlraums had a calculated asymmetry originating from a jet caused by the liner; (2) the gas-filled hohlraums were found to have a measured symmetry shift with unsmoothed beams, which had not been predicted but could be tuned out; and (3) under some conditions, large scattering levels were measured with unsmoothed laser beams. These latter two effects resulted in the specification of the beam-smoothing requirements for the NIF. In addition, in 1990 there were far fewer experimental data and a more rudimentary modeling capability for the NIF targets than now exist. Developing an integrated modeling capability with full radiation transport, developing the experimental and diagnostic techniques required to quantitatively evaluate target performance, and developing a variety of capsule materials along with demonstrating smooth cryogenic layers, have all represented significant challenges to the NOVA team, the national ICF program, and the NIF project. The fact that the level of technical sophistication has increased so dramatically during the past 6 years, with only a modest impact on the laser and target requirements for the NIF, increases confidence that the NIF will achieve its ignition goals.

A second approach to assessing the likelihood of achieving ignition and propagating burn is to examine the NIF's flexibility should the physics turn out to be different from what is currently expected. For example, target designs are being developed that would, according to integrated two-dimensional calculations, ignite with incident laser light with an energy around 1 MJ. Since the NIF is designed to

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[2] National Research Council, *Review of the Department of Energy's Inertial Confinement Fusion Program: Final Report*, National Academy Press, Washington, D.C., September 1990.

routinely deliver 1.8 MJ, these designs accommodate variations in laser entrance hole or hohlraum size that might be desirable for easier control of symmetry, or for compensation of the observed variation in stimulated scattering or the uncertainties in x-ray conversion and wall losses. Most plausible variations in the physics database, such as the capsule equation of state or opacity, are performance-neutral. The surface finish on the capsules might also be improved relative to present NOVA capsules if this is required to help suppress hydrodynamic instabilities. In addition, other capsule materials under development, such as Be and B_4C, can reduce the growth of hydrodynamic instabilities and are less sensitive to roughness of the cryogenic fuel layer. Operation with somewhat lower-temperature hohlraums, while requiring a laser energy at the upper end of the NIF operating range, would reduce the effects of laser-plasma instabilities.

The major differences between the present NIF design and the concept envisaged in 1990 have resulted from modifications to the target chamber, the target area, and the front end of the NIF to incorporate direct-drive capability. The likelihood of ignition and burn propagation through direct drive has increased significantly since 1990 owing to better understanding of both laser-beam imprinting and the growth of hydrodynamic instabilities. By an optimal choice of port locations for indirect drive, the direct-drive geometric requirements can be met by moving one-half of the NIF beams to 24 new beam ports that have been added to the chamber. The detailed requirements for beam smoothing await the results of experiments over the next several years on OMEGA and NIKE. Space has been provided in the NIF front end to implement one or more of the wide variety of beam-smoothing techniques now being evaluated. A further illustration of the NIF's flexibility is that the direct-drive beam configuration also allows a more nearly spherical (tetrahedral) hohlraum to be used.

The campaign to achieve ignition with the NIF will certainly be the most challenging ever undertaken by the national ICF program. However, given the success in the indirect-drive target physics campaign on NOVA over the past 6 years and the flexibility of the NIF design, the ignition and burn propagation objectives of the NIF will likely be achieved, but cannot be guaranteed.

4

Technological Readiness

NIF LASER TECHNOLOGY

The proposed NIF rests on the progress in solid-state lasers that started with 1-J pulses from the Ruby laser in 1960 and extends to the present 40-kJ-level output from NOVA. This 40,000-fold increase in some 30 years is based on progress in the fundamental understanding of laser-host materials, on optimizing laser architecture for energy extraction, and on mitigating nonlinear effects that reduce beam quality and limit beam peak power. The NIF laser driver was proposed and designed to ignite a target by providing more than 1 MJ of pulsed energy at 350 nm. Further, the laser source is to be a reliable tool for laser-target studies, with adequate flexibility to control such important parameters as pulse shape, spectral properties, spatial smoothing, and pointing. The proposed NIF laser is based on a new architecture that reduces the number of optical elements, reduces the volume, and enhances the control and operational capability through a design that allows repair of laser beamlines between shots.

To test these advanced concepts, a single laser beamline, called the Beamlet, was constructed. The Beamlet has been operational since 1994 and has provided a test bed for the NIF architecture and design, including operation at the fluence levels of the NIF laser. It has proven the multipass oscillator/amplifier concept and shown that the potassium dihydrogen phosphate (KDP) plasma electrode polarization switch operates as expected. The Beamlet has also demonstrated the use of a diode-pumped fiber laser oscillator as the master oscillator for the more complex 192-beamline NIF, stability against small-scale self-focusing through relay imaging and spatial filtering, the advantages of an active mirror to control wavefront quality, and high nonlinear frequency-conversion efficiency for third-harmonic output at 350 nm.

NIF Laser Design Goals and Ignition Requirements

The NIF laser (Figure 2) has a design peak performance of 2.2-MJ at 600-TW peak power. It consists of 192 beamlines, arranged into four arrays. Each array is composed of 4 × 12 segments, each with an aperture of 40 × 40 cm^2. The baseline operation is set at 1.8 MJ and 500 TW, at 350 nm. The NIF design was selected from two conceptual designs based on multipass architecture. An original 240-beamline design was deferred and the current design with 192 beamlines was selected as a compromise, based on a reasonable expectation of reaching ignition with the lower energy and power and associated cost trade-offs.

The NIF baseline design has a laser architecture selected to meet the required performance levels at acceptable cost while respecting the limits imposed by laser fluence damage. Peak fluence from a 4-pass amplifier through the optical beam path to the KDP harmonic-conversion crystal remains below the damage fluence of the optical elements, if they are procured from the highest-quality fabrication. The baseline design uses lower-cost components that can be more readily mass produced but have yet to meet the required damage thresholds. Optical damage can limit laser performance and facility reliability and is further discussed below.

The NIF laser performance goal was based on extensive target studies using the NOVA facility and studies at the Nevada Test Site. The latter tests, in the 1980s, proved the concept of ICF. That result, coupled with laser/target-interaction studies and computer simulations, determines a probable ignition regime in a peak-power vs. total-energy plot (Figure 3). The regime is bounded above by laser-plasma instabilities and below by hydrodynamic instabilities. A selected target design and predicted ignition point are shown. Figure 3 also shows the baseline and maximum safe-operating levels of the

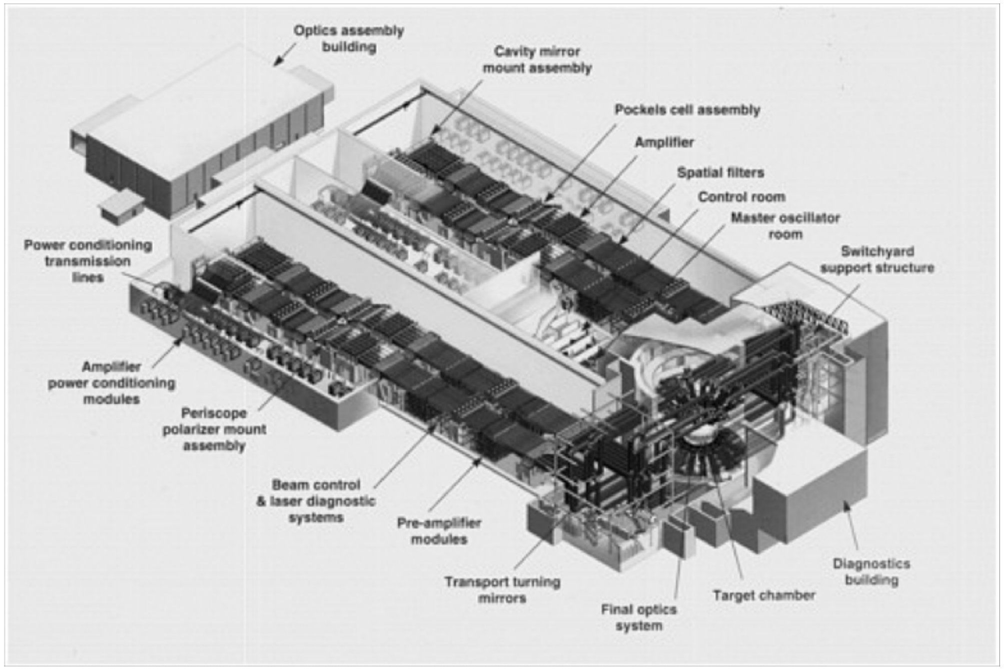

Figure 2 Schematic overview of the proposed National Ignition Facility.
Source: Department of Energy.

NIF. The NIF laser design provides an estimated factor-of-two safety margin above the estimated ignition threshold.[1]

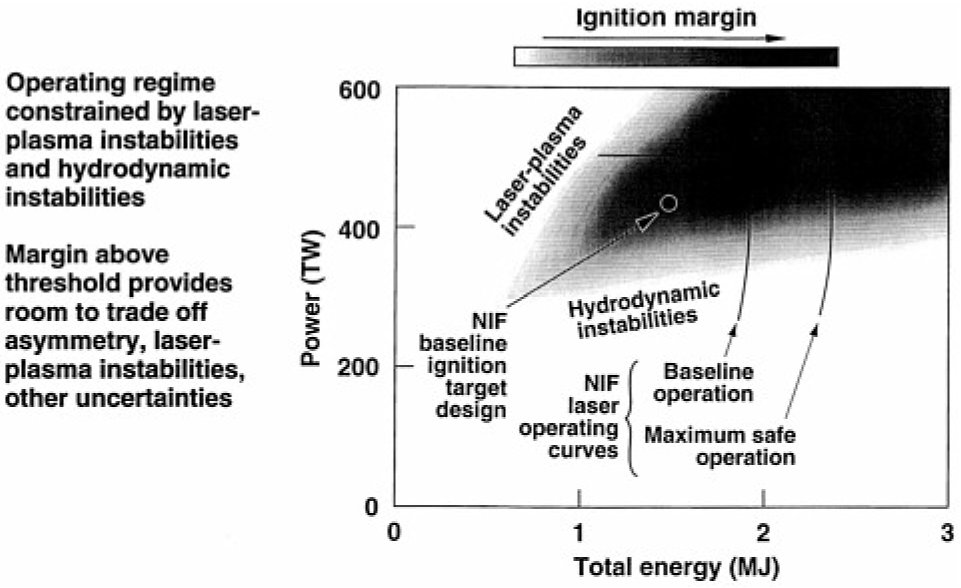

Figure 3 Target ignition regimes plotted vs. peak power in terawatts and peak energy in megajoules. The laser plasma and hydrodynamic instability regions are indicated. An ignition target design is indicated along with the National Ignition Facility baseline and maximum safe operating power-energy curves. Source: Lawrence Livermore National Laboratory.

Beamlet Performance as Validation of the NIF Design

The NIF laser will operate with larger optics than any previous laser system. Figure 4 shows schematics of the NIF and the Beamlet laser designs. The two designs are substantially similar, with minor differences in the size of the optical components, the injection into the 4-pass laser amplifier, and turning mirrors between the NIF laser and the harmonic converter. Figure 5 shows the comparison of the Beamlet performance and the expected NIF beamline performance at 1050 nm. The Beamlet operates over the peak power/pulse-energy region projected for the NIF,[2] with recent experience demonstrating the expected performance. The Beamlet has operated at the intensity/output-fluence levels projected for a NIF beamline, for pulses from 1 ns to 10 ns, and has exceeded the nominal NIF operating point.[3]

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[1] S.W. Haan et al. "Ignition Target Design for the National Ignition Facility," *Inertial Confinement Fusion*, UCRL-LR-105821-95-4, Vol. 5, No. 4, p. 215–225, 1995.

[2] LLNL ICF Program, presentation to NIF Laser Subcommittee, Inertial Confinement Fusion Advisory Committee/Defense Programs (ICFAC/DP), L-17459, Vol. 2, April 20–23, 1994.

[3] LLNL ICF Program, presentation to National Research Council's Committee for the Review of the Department of Energy's Inertial Confinement Fusion Program (U), L-22838-01, August 1–2, 1996.

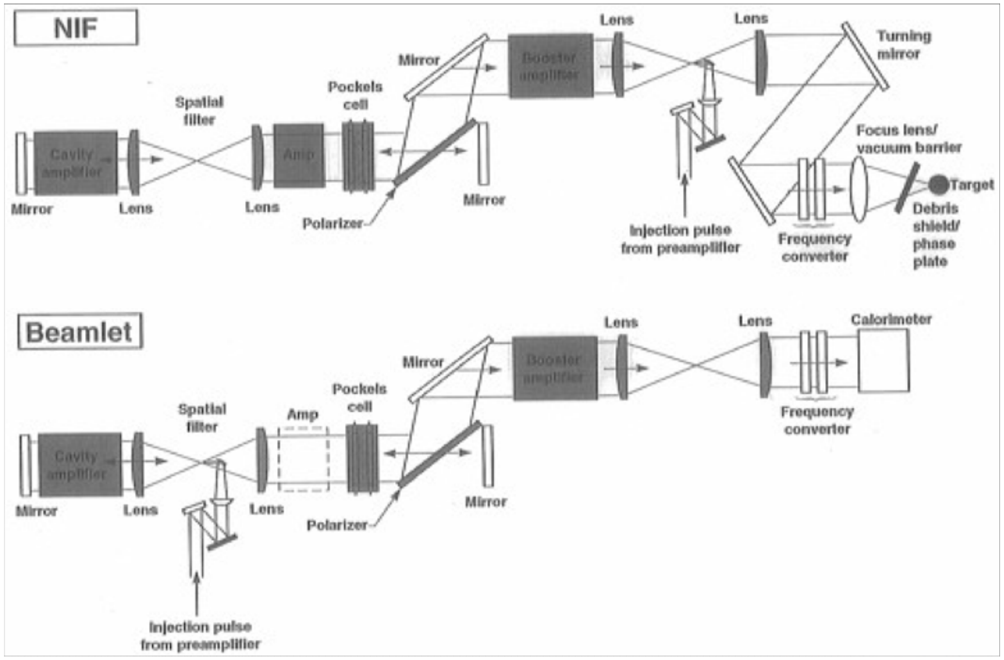

Figure 4 The NIF beamline and the Beamlet beamline layout Source: Lawrence Livermore National Laboratory.

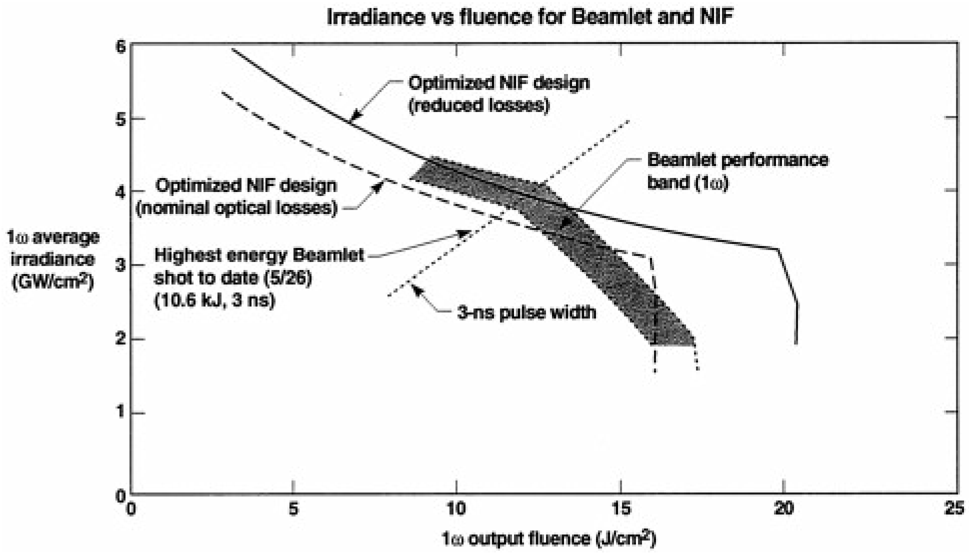

Figure 5 Comparison of the Beamlet and the NIF performance levels.
Source: Lawrence Livermore National Laboratory.

Performance, Cost, and Optical Damage

With cost strongly dependent on the maximum allowed optical fluence of components along the laser optical beam path, the NIF laser is designed to operate at the maximum fluence consistent with reliability and projected performance. Further, significant efforts have been made to raise the fluence-damage threshold of the optical components, to increase laser performance, and to reduce cost. Improvements have been made and the NIF is expected to operate at a fluence level approximately twice that of NOVA. The component nearest the damage fluence limit is the KDP tripler crystal, which becomes the "fuse" of the optical train. Efforts are continuing to improve the damage threshold of this component, although it already exceeds the NIF requirement of 17 J/cm^2, with measured damage thresholds between 17 and 25 J/cm^2 at 350 nm in the highest-quality crystals, which are slow-grown using the most expensive technology. If the mass-produced KDP crystals from the lower-cost, rapid-growth technology currently under development do not meet the damage threshold requirement, the more expensive and time-consuming process will be used and can be accommodated within the current schedule and cost contingencies.

A program has been instituted to work with optical component vendors to further increase damage-fluence values by improving finishing methods. However, damage is a probabilistic phenomenon, initiated at the atomic scale or by bulk or surface impurities. Thus, future improvements in damage fluence cannot be predicted, and the prudent design should recognize the measured damage limits and operate within that constraint. The NIF laser has been designed to operate below proven damage levels of the optical components in the beamline path.

Laser Architecture

The NIF laser design utilizes a master oscillator-preamplifier, followed by a 4-pass amplifier with a polarization switch, followed by a booster amplifier. Compared to the NOVA linear-amplifier, this architecture has the advantages of compact design, fewer optical components, and reduced optical fluence along the beam path. The Beamlet laser was constructed at the scale of a NIF beamline to test the multipass amplifier architecture and the components of the NIF laser in a nearly full-scale system.[4]

Master Oscillator—Preamplifier

The master oscillator must be flexible in both wavelength generation (for bandwidth control) and in pulse-width generation (for temporal pulse shaping). Since 192 master oscillators are required for the NIF, followed by 192 preamplifiers to boost the energy to the near-10-J level prior to injection into the multipass amplifiers, a diode-laser-pumped master oscillator concept was selected as the master-oscillator design for the NIF.

The Beamlet master oscillator (MO) incorporates optical elements similar to those that would be used in the NIF MO. The Beamlet MO uses a diode-pumped laser, followed by an integrated optical modulator and a high-gain regenerative amplifier to provide output energy in a spatially and temporally controlled pulse shape. This MO output is then amplified in a flashlamp-pumped Nd: glass multipass preamplifier. The Beamlet MO has demonstrated the required pulse-shaping capability. It has also demonstrated bandwidth control capability by the generation of multiple wavelengths.

The experience with the Beamlet MO should reduce the risk for the NIF MO implementation, which is based on a diode-laser-pumped Yb:glass fiber-ring oscillator, followed by a regenerative amplifier and 192 10-J preamplifier modules. The NIF preamplifier is a flashlamp-pumped Nd:glass slab-geometry laser, with 4-pass amplification of the input waveform. The alternative of using a diode laser to pump the preamplifier was investigated, but the high cost of laser diode arrays currently prevents their use.

Multipass Amplifier-Booster Amplifier

A multipass amplifier using polarization switching and a 4-pass geometry was selected to reduce cost and yet provide the required energy with proper spatial and temporal beam shaping. Further, the amplifier design allows flexibility in the spectral content of the beam (both for SSD and for spectral chirping followed by compression to achieve higher peak power). Figure 4 shows a schematic of the 4-pass amplifier, as implemented on the Beamlet and as proposed for the NIF. The advantages of the multipass design include the need to purchase fewer of the largest optical components than in a traditional single-pass MO power amplifier design. The multipass amplifier design, however, requires the development of a large-aperture Pockels cell electrooptic switch that has good hold-off to prevent preoscillation and has high switching efficiency to maintain overall laser efficiency.

Injection

The 10-J preshaped input beam is injected through an aperture at the focal region of the vacuum spatial filter. Temporal and spatial preshaping is required to obtain the flat-top super-Gaussian output profile from the amplifier. The input beam is reflected from a deformable mirror that presets the wavefront to counter beam distortion in the 4-pass amplifier. In the Beamlet, injection takes place in the oscillator spatial filter. In the NIF, injection would take place prior to the booster amplifier to exploit the gain of the booster amplifier and to use the deformable mirror to correct distortions created by the booster amplifier.

The input beam is shaped in time to counter the effects of the amplification, in which the amplifier saturates for efficient energy extraction. Thus, the power of the input pulse rises in a carefully

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[4] J. Campbell (ed.), *Inertial Confinement Fusion*, UCRL-LR-105821-95-1, Vol. 5, Oct.-Dec. 1994.

controlled manner over a period of nanoseconds. The result, following amplification, is a shaped beam that meets the temporal target-illumination profile goal. The input beam is also spatially shaped to counter the higher amplifier gain at the edges compared to the center; the input beam to the amplifier has higher power around the perimeter to give a flat-topped beam after amplification.

Amplification

The amplifier consists of Brewster-angle glass-gain elements pumped by flashlamps. The main amplifier has 11 slabs, and the booster amplifier has 5 slabs, with a glass volume of 12 liters/slab. The Beamlet stores 35.65 kJ of energy in its main amplifier and 15.97 kJ in its booster amplifier. The amplifier is operated at an extraction beam to amplifier slab area ratio, or apodized "fill factor," of 90%; the NIF beamline design calls for operation at a fill factor of 94%.

Spatial-mode Filtering

The peak output power of the multipass amplifier is limited by changes in the induced nonlinear index of refraction. These changes can lead to small-scale self-focusing and peak intensities that exceed the dielectric strength of the optical components. Relay imaging, coupled with spatial filtering, has been developed to counter the onset of self-focusing. Measurements and modeling of these phenomena have agreed, giving the designers confidence that small-scale self-focusing can be prevented under normal operating conditions.

Pockels Cell Switch

The 4-pass amplifier geometry is critically dependent on a large-aperture Pockels cell switch. The Pockels cell optical switch consists of a KD*P (deuterated KDP) electrooptic element within the laser resonator. The KD*P switch rotates the plane of polarization of the laser beam to provide for additional passes through the amplifier, prior to switching the polarization direction for output coupling from the dielectric-coated polarizer. The successful development of the plasma electrode Pockels cell (PEPC) KD*P switch has allowed the 4-pass amplifier to move to the experimental-demonstration phase. The KD*P switch meets the optical-switching-efficiency goal of greater than 99.5%.

Deformable Mirror

The operation of the Beamlet line shows that the lamp-pumped slab amplifiers are the largest source of wavefront distortion. The distortion (beam-wavefront curvature and tilt) is induced by the thermal loading of the slab following pumping by the flashlamps. In the Beamlet, the beam distortion is controlled by presetting a 23-element deformable mirror prior to each shot. In the NIF beamline, the deformable mirror would be placed at the back mirror reflector position of the 4-pass amplifier and would be $40 \times 40\ \text{cm}^2$ in area.

Harmonic Generation

The technology for harmonic conversion using Type I second-harmonic generation, followed by Type II sum-frequency generation to the third harmonic output, is being applied to the NIF laser. KDP crystals required for the NIF frequency conversion are being grown both by a rapid-growth technique (which has not yet produced crystals meeting the NIF damage threshold requirements) and by the well-developed traditional solution growth approach. Experiments using the Beamlet have confirmed the conversion efficiency of the KDP crystal arrays. As mentioned above, the fluence incident on the KD*P harmonic converter is just below the damage threshold such that the KD*P crystal acts as the optical fuse in the NIF-beamline system.

Related Laser Experience

The LLE operates the OMEGA laser system. The laboratory has explored direct-drive target physics with the goal of determining whether the NIF has the potential for ignition via direct drive. Direct drive places tight tolerances on the laser system in beam smoothing, power energy balance, and beam temporal shaping.

Approaches to laser-beam smoothing were explored at the Naval Research Laboratory (NRL) 1983, using induced spatial incoherence (ISI). Beam smoothing by spectral dispersion (SSD) was explored at LLE in 1989. Together, these two techniques can control the laser beam at the target, providing a time-integrated smooth beam that reduces plasma instabilities for indirect drive and reduces laser imprinting on the target for direct drive.

The ISI approach to beam smoothing has been demonstrated on the broadband KrF NIKE laser at NRL. The broadband laser source gives rise to a change in the speckle pattern for a time inversely proportional to laser bandwidth. SSD uses diffraction to spatially translate different frequency components of the laser beam. Again, the speckle pattern changes with a time proportional to the inverse bandwidth of the laser source. Beam smoothing by SSD is better suited to solid-state lasers. An extension of SSD uses gratings in both directions transverse to the beam-propagation direction. Two-dimensional SSD has been demonstrated by the OMEGA laser system. The triple-frequency laser beam was made spatially homogeneous using a continuous digital phase plate, or kinoforrn phase plate (KPP). The two-dimensional SSD was demonstrated in the ultraviolet to provide beam smoothing. The technology for KPP generation, using 16 level phase steps, should meet the focal plane requirements on the NIF beam.

TARGETS

ICF targets are designed in accord with a detailed experience base, augmented by extensive simulation calculations that integrate, to the extent feasible, all aspects of the ICF process:

- Laser pulse energy, including frequency, temporal, and spatial characteristics;
- Hohlraum. geometry, materials, gas-fill (if any);
- Target design, fabrication specifications, suspension system; and
- Diagnostics integration.

Actual target fabrication relies on specialized technology and capabilities whose realities and limitations define a large number of the challenges of the ICF program. A baseline target design is in place and was used to determine the necessary operating parameters for the NIF. Possibilities for new and better targets, which would increase the likelihood of ignition, are being explored with the aid of recent advances in computational capabilities and related experiments. New ideas are being proposed regularly, including "cocktail" walls, different shapes for hohlraums, and new materials for capsules. The possibility that new and better targets might be developed before actual NIF operation in 5 or more years should not be discounted.

Hohlraum Design and Fabrication

In indirect drive, the irradiated capsule is placed in a thin, high-Z hohlraum, whose interior absorbs the laser irradiation and confines the x-ray irradiation field that heats and ablates the outer capsule layers, driving the implosion. Hohlraum designs have evolved to accommodate multiple-ring laser illumination in order to enhance the uniformity of energy deposition on the targets. A gas-fill option is intended to mitigate stagnation of ablated wall material on the hohlraum axis, and specialized designs can accommodate a host of diagnostics. At this writing, progress and technological readiness in this area are good.

Hohlraum designs are expected to evolve and be tested to accommodate the anticipated extension to cryogenic target capsules. Even though they are not part of the NIF baseline target design, future design and fabrication work may well explore noncylindrical hohlraum geometries (e.g., tetrahedral) that might produce greater uniformity in the capsule drive. Such geometries could be explored in the 60-beam OMEGA facility, which provides a laser-illumination field intermediate between the present 10-beam NOVA and the proposed 192-beam NIF.

Capsule Fabrication

Capsule design and fabrication specifications are closely related to the expected dynamics of the various hydrodynamic instabilities during the implosion phase, with trade-offs between required laser-irradiation, hohlraum, and capsule-fabrication specifications. In particular, capsule-fabrication specifications depend on the capsule design, material properties such as density uniformity, and surface-finish spectra (an initial amplitude is more serious in some modes than in others), and the irradiation field. Generally, doped-CH ablator shells require surface finishes of some 20 nm rms (for mode numbers >10) and can accommodate surface roughness up to 500 nm rms in lower modes. The HEP 4 experiments on NOVA used these specifications as a baseline. The technology for NIF-scale target fabrication is currently under development. Surface-finish specifications for beryllium ablators are estimated to be typically 2 to 3 times more forgiving. The fabrication technology for beryllium ablator shells, however, is not as advanced as that for plastic: either small fill holes, or seams between hemispherical capsule segments, or other means that would provide some material porosity are required for the deuterium-tritium (DT) fill. Issues of material-density uniformity also arise, depending on the materials and fabrication methods employed, and are still under study and development. [5]

Although not all issues have yet been resolved, continuing experiments and simulations are expected to further define fabrication specifications. Given the evolution of the scientific understanding of hydrodynamic instability dynamics and the coupling between drive uniformity and capsule fabrication specifications, continuing progress in this area will increase the likelihood of achieving ignition on the proposed NIF.

Cryogenic Capsule Technology

Present NIF capsule designs include a high-density (solid), cryogenic DT fuel layer inside an ablator shell, containing a gas-phase DT core. Three important technology issues are currently outstanding. The first is related to the assembly/fill mechanics and resulting solid/gas surface finish. Interfacial-surface smoothness to about 1 µm has been demonstrated with beta-layering.[6] The second is related to the mechanics of handling such capsules, from fabrication to installation in the target chamber, and laser irradiation. The third concerns methods for characterization of the fuel (compositional and physical uniformity) in optically opaque capsules (such as those fabricated from Be). A program is under way to address the first of these, and the second is now under consideration.

Such cryogenic targets are in an advanced stage of development because they will be required at the OMEGA laser within the next few years. While the deployment at OMEGA cannot be identical to that proposed for the NIF, invaluable experience will be gained before final NIF engineering is necessary. Although it is reasonable to expect that the target uniformity required will be achieved when it is needed, targets are of such great importance for the goals of the NIF that the progress in target fabrication should continue to be encouraged and monitored.

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[5] J. Lindl, LLNL, private communication.

[6] Beta-layering is a process that uses preferential local heating by beta-decay in frozen deuterium-tritium mixtures to anneal surface non-uniformities.

DIAGNOSTICS

The present suite of ICF diagnostics is the result of an intense and creative 25-year effort that proceeded in relative isolation because of both classification and the unique high-energy-density environment involved. Measurements enabled by these diverse diagnostics have played indispensable roles in tests of various kinds, in support of SBSS and ICF technology development, in experiments that probe fundamental ICF physics, and in code-validation experiments. A commitment to the continuing development of this component of the ICF program is crucial to the success of the NIF and SBSS.

ICF diagnostics can be grouped into three broad categories: laser characterization, hohlraum characterization, and capsule performance. These three classes may be further categorized as facility-provided and experiment-specific. Most diagnostic modules conform to standard mechanical, electrical, and data interfaces, and many can be used on either the NOVA or the OMEGA facilities. A similar philosophy of design standardization has been adopted and should be encouraged for the NIF and, indeed, at comparable facilities now being planned outside the United States.

Laser characterization diagnostics are used to measure such attributes as laser pointing, focusing, synchronization, temporal pulse profile, and back-scattered light. Hohlraum diagnostics are used to measure the history of hohlraum temperature and the spatial symmetry of the radiation drive. Some of these have also been used in experiments conducted at other ICF facilities. Capsule diagnostics have benefited from a variety of developments. These include a gating technology for micro-channel plates that allows nearly continuous, time-resolved (~50-ps intervals), two-dimensional x-ray imaging of imploding capsules. Such high-speed gating has reduced motional blurring of imaged ICF targets. Areal density images with high spatial resolution (~10 µm) and temporal resolution (~100 ps) can also be recorded using customize x-ray backlighting, which exploits a host of backlighter materials to vary the x-ray spectrum and can be timed, as necessary, through independent control of the backlighter beam(s). High-density plasmas can be imaged and diagnosed using x-ray laser interferometers.

Some nuclear diagnostics are currently in use, and others are being developed. These are necessary to probe the behavior of the capsule-core region and, as ignition is approached, to provide data from imploding capsules. Present and planned ICF capsule diagnostics are designed to record such quantities as neutron yield (^{63}Cu activation), fuel-ion temperature (neutron time of flight), ignition time and fuel-burn history (fusion neutrons or -rays), imploded core image (neutron imaging), fuel areal density and implosion symmetry (tertiary neutrons or protons), and time-resolved fuel ion temperature (n-p recoil). Other diagnostics are also under consideration, such as a -to-Cerenkov conversion technique for burn-history measurements.

Despite the generally healthy state of diagnostics, many challenges remain. Further developments will be necessary to support the drive tuning (pointing, timing, and pulse shaping of the laser beams) necessary to achieve ignition on the NIF. Also needed will be diagnostics to characterize time-dependent radiation drive uniformity within the hohlraum volume, and to image with better spatial (5-10-µm) and temporal (<20-ps) resolution. New technology for post-ignition diagnostics that can survive the resulting harsh environment (debris, electromagnetic pulses, radiation) on the NIF will also be needed.

Multidimensional data-acquisition and imaging techniques (e.g., multiaxis tomography) can be expected to provide new types of data and should continue to be developed. Progress should also be encouraged in replacing photographic film with imaging detectors that have better efficiency, linearity, and dynamic range. Diagnostics to probe two-and three-dimensional unsteady hydrodynamics, developed both for ICF and other applications, will yield new data that will both advance understanding and validate simulations of these phenomena. The latter is particularly important, in view of the extension of numerical simulation capabilities enabled by the emerging ASCI machines.

The development of ICF diagnostics will be coordinated by the Joint Central Diagnostic Team formed among the National Laboratories. This group is charged with defining requirements, selecting and developing diagnostics, and integrating the diagnostics into the NIF program. Each laboratory will have lead primary responsibilities funded under its ICF program funds. Other research groups are also contributing to this effort, as the community of ICF-facility users further expands to universities.

THE NATIONAL IGNITION FACILITY PROJECT

Project Organization

The NIF project organization and its relationship to the LLNL appear to be sound and acceptable. In place are the elements that are critical for optimizing the chances for successful project implementation and completion, including the following:

- The project has support from DOE management. There is a clear chain of command as well as a method of appeal to address problems and break logjams, with laboratory management fully committed to the project.
- At the start of the Title I process, the work breakdown structures and project organization structure were in place and aligned to provide clear technical interfaces. This structure was tested during the Title I process.
- The project manager has sufficient administrative autonomy to accomplish work in a timely, efficient manner. This includes a $25 million procurement authority that resides at LLNL to facilitate the procurement of necessary items with a minimum of red tape. The procurement authority alone is a significant step. In addition, a number of procurement specialists have the NIF as their first priority. The dedicated legal support available to the project is also helpful.
- The project is led by an appropriate number of competent project leaders and engineers. This leadership will facilitate good and frequent communication among the leadership team and allow issues to be dealt with effectively.
- Twenty-eight design basis books describe in detail all the special equipment items to be built. Interface control and a Baseline Change Control Board are in place to maintain the integrity of scope, cost, and time line.
- There is a project tracking system commensurate with a maximum expenditure rate of about $20 million per month. This tracking system is quite detailed, with the project broken into procurement packages. There are cost accounting plans with schedule milestones that allow close monitoring of progress based on completed activities. The relatively large number of milestones to be measured allows an objective assessment of progress.
- The project leadership has a good relationship with both DOE Oakland and DOE headquarters, a prerequisite for effective project management. That relationship will prove essential in resolving any unanticipated variances about the original scope, cost, and time line.

Title I Review

Based on the design basis books and the interface controls in place, a preliminary design (Title I) was done, and LLNL formed a number of committees to conduct a review; these committees include both internal and external experts. The review was a complete and stringent process involving 96 professionals with expertise in all of the relevant areas (facility expertise: 20 members; laser system expertise: 38 members; target area expertise: 18 members; systems control expertise: 9 members; optics expertise: 5 members; and operations expertise: 6 members). The results of this Title I review are now the baseline for the project and are reflected in the Schedule 44 for FY98.

Cost Estimates

To date there are two complete independent cost estimates (ICEs) for the NIF project: the 1994 estimate based on the preliminary design (reflected in the Schedule 44 for FY97), and the 1996 estimate based on the results of the Title I review (reflected in the Schedule 44 for FY98). The total estimated cost (TEC) of the original project remains the same within the uncertainty of the estimating methods. However, the FY96 cost estimate includes an additional $29 million for site-specific costs and $125 million of additional scope compared to the 1994 estimate, resulting in a net increase of $154 million. However, the TPC has increased by only $74 million, because the start-up costs (and the scope of work associated with them) have been reduced from $77.5 million to $7.1 million. Most of the start-up costs have been moved to the LLNL-projected operating budget for NIF and NOVA operations. In addition, there are NIF-related non-TPC costs of $397 million in LLNL-projected operating funds in FY98-FY02. The contingency has also been reduced from S $144 million (20.6%) to $127 million (14.6%). In addition to the TPC, non-TPC funds of $120 million (FY98-FY02) are planned for R&D in optics and laser technology. LLNL plans to use these funds to perform R&D and to qualify vendors to the point that a 14.6% contingency becomes acceptable.

The start-up funding in the FY96 cost estimate of $7.1 million within the TPC is sufficient to test one bundle of lasers (4% of the full facility). The remaining start-up costs necessary are included in the NIF portion of the NOVA/NIF operating costs ($175 million in FY99-FY02). To make these funds available to the NIF presupposes that NOVA operations are shut down, curtailed greatly, or supported from other sources at the end of 1998, which may hinder the pursuit of the remaining hurdles discussed in Chapter 5.

The operating budget for the target physics program includes diagnostics and instrumentation not included in the TPC, as well as other items such as modeling. Of the $155 million projected for these activities (FY99-FY02), about $102 million appears relevant to the NIF. The committee notes that these are LLNL/NIF projections of additional operating funding.

In summary, the projected costs relevant to the NIF through construction consist of the TPC at $1.148 billion, with additional non-TPC costs in the LLNL-projected operating budget: $120 million for optics and laser R&D, $102 million for diagnostics and instrumentation, and $175 million for start-up costs and other R&D.

Independent Cost Estimate Review

An independent cost estimate review was contracted by DOE headquarters to Foster Wheeler, a company that has no other responsibility in the project. An ICE with contingency was completed in 1994, as reflected in Table 3. The committee notes that the TPC of 1994 did not include any site-specific costs; $29 million must be added to the 1994 TPC to make it site-specific to LLNL. A second ICE review took place in 1996; the final report was pending at the time this report was drafted. The Schedule 44 FY98 TPC and the 1996 ICE review reflect the results of the Title I review and a more complete

Table 3 NIF Cost and Contingency Data (Actual $M)

	Schedule 44 (FY97)	ICE 94	Schedule 44 (FY98)	ICE 96
TEC ($ M)	843[a]	834	997[b]	
TPC ($ M)	1074[a]	1034	1148[b]	1150
Contingency ($ M)	144	143	127	
Contingency (%)	20.6	20.6	14.6	19

[a] Site-specific costs need to be added, ranging from $29 million to $130 million, depending on the site. The LLNL site adds $29 million.)

[b] Additional scope ($125 million) is included as discussed in the text.

design. An additional $125 million in scope was added to the project between the 1994 and 1996 ICE reviews, including direct-drive capability, a radiation effects testing option, flashlamp cooling to increase shot rate, smaller spot size capability, and beam-smoothing capability.

Table 4 LLNL-Projected NIF-Related Funding

FY98 ($ M)	FY99 ($ M)	FY00 ($ M)	FY01 ($ M)	FY02 ($ M)	Subtotal	NIF Related Total ($ M)
Additional non-TPC funding (Operations, NOVA, and NIF)						
	30	40	50	55		175
Additional non-TPC R&D funding (optics and laser technology)						
40	40	20	10	10		120
Target-Physics Program[a]						
	25	40	40	50	155	102[b]
				TOTAL		**397**

[a] Includes scope (e.g., experimental diagnostic instrumentation) not included in TPC.

[b] Assumes that two-thirds of the subtotal is relevant to the NIF.

Table 3 contains NIF cost and contingency data, and Table 4 gives LLNL projections of non-TPC funding available for technology development and R&D that is currently the mission of the ICF program and necessary for the NIF.

Contingency Analysis

A contingency of about 15% is adequate for conventional facilities. However, special equipment that requires a great deal of R&D, technology development, and vendor qualification carries a greater risk, so that 25 to 35% at this stage of the NIF project is more realistic. The present overall contingency rate of 14.6% thus seems low. However, in accord with ongoing funding received by LLNL for the laser technology development mission, the TPC has been defined more narrowly, with much of the necessary R&D covered in specific areas outside the TPC, as detailed in Tables 3 and 4. These additional funds projected by LLNL will advance the technologies and qualify vendors to the extent that a 14.6% contingency is self-consistent.

Operating Cost

High-technology facilities usually require between 10 and 13% of the TPC to fund operations each year after the facility is fully operational. For a TPC of $1.148 billion, the expected operating budget would be $115 million to $150 million. LLNL projects a NIF operating budget of $60 million, with an additional $60 million provided by the target physics program (NOVA, OMEGA, NIF) to cover some of the facility's experimental operation in FY03, for a total of $120 million to cover the facility's experimental operation in FY03.

Looking more precisely at the narrowly defined "operating budget" (that is, without the target physics program contribution), NIF project personnel provided the committee with detailed documentation on the operating budget and the procedure used for the bottom-up collection of judgments on operating budget requirements from skilled practitioners on NOVA. Although the NOVA personnel are the best qualified people to do the bottom-up input, the NIF is a significantly larger facility than NOVA and the experience of the NOVA personnel may lead them to underestimate the operational complexity.

NIF project personnel also provided data on the NOVA operating budget as a percent of TPC. The initial operating budget for NOVA in 1986 was $10 million ($6 million for personnel and $4 million for consumables) or about 6% of the NOVA construction cost of $176 million in as-spent dollars. That NOVA operating budget corresponds to about $17 million in 1997 dollars, which is indeed the NOVA operating budget in 1996. The NOVA operating staff consisted of 28 professionals and 49 technicians in 1986 and consisted of 6 professionals and 56 technicians in 1996. The current NIF operating staff includes 260 people, which is consistent with the $60 million operating budget.

The committee notes that the apparently low proposed direct operating budget of $60 million appears compatible with NOVA experience, and that with the additional $60 million projected in the target physics program the total funds available ($120 million) are consistent with the 10 to 13% expected from experience of similar megaprojects.

5

Remaining Hurdles

Several technical issues should be pursued in parallel with NIF construction. While none is sufficiently serious to constitute a "showstopper," continued attention to all of them will help to ensure the NIF's success and its contributions to SBSS.

- **Consistent physical understanding of NIF-relevant phenomena.** Efforts should continue to better understand the requirements for convergence and compression with a modified NOVA configuration (HEP 5), laser-plasma interactions and the resulting "spot motion," the effects of hohlraum wall motion and the physics of plasma instabilities in gas-filled hohlraums, and the prediction, control, and diagnostics of the x-ray drive in hohlraums. Experiments to be conducted include the following:

  1. Complete the 10-beam smoothing and wall-motion experiments in gas-filled hohlraums on NOVA. Implementation of the full smoothing by spectral dispersion (SSD) and random phase plates (RPPs) on all 10 beams will demonstrate further understanding of the potential limiting effects of laser-plasma interactions. Demonstrated low levels of stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS), and the resulting acceptable radiation temperatures, are expected.
  2. Conduct experiments on retarding wall motion with improved azimuthal symmetry and a wider range of plasma conditions to further investigate the NIF hohlraum design.
  3. Vigorously pursue experiments to study the behavior of Rayleigh-Taylor and Richtmyer-Meskov hydrodynamic instabilities in converging geometries.

- **Need for and challenges of three-dimensional simulations.** Current three-dimensional computer codes are inadequate for integrated calculations of ignition; their improvement will contribute significantly to increasing the probability of ignition. These codes must be adapted to run on ASCI platforms. The development of new, less empirical three-dimensional models and algorithms is necessary, as is benchmarking of three-dimensional codes by ICF experiments and test data. This effort is further challenged by the different characteristics of the machines purchased under the ASCI program.
- **Cryogenic capsule technology.** Advances should be sought in assembly, fill, and surface smoothness. Continued development of handling and delivery systems is also important to ignition, as are methods of characterizing the fuel in optically opaque cells. Researchers should explore target-design alternatives, advance target design and fabrication technology, and pursue cryogenic target experiments on OMEGA.
- **Optics damage thresholds and cost.** While the current cost estimate contains funds to purchase slow-growth KDP crystals if necessary, the effect on schedules must be considered if the fast-growth crystals fail to meet damage threshold requirements.

6

Findings and Conclusions

THE NIF WOULD MAKE IMPORTANT CONTRIBUTIONS TOWARD THE STATED LONG-TERMGOALS OF THE SBSS PROGRAM

The proposed NIF is a flexible, high-power, high-energy laser facility that will address fundamental high-energy-density physics issues while creating in the laboratory conditions approaching those relevant to a nuclear weapon. The challenge of achieving ignition should help attract and sustain a cadre of talented scientists and engineers with weapons-relevant experience and expertise. The challenge of *predicting* results of NIF experiments will provide a certification of future weapons stewards analogous to that provided by the underground test experience of the present designers. The NIF's experimental capabilities will complement other SBSS activities by allowing unique experiments probing weapons-related physics.

THE SCIENCE AND TECHNOLOGY HAVE PROGRESSED SUFFICIENTLY TO ALLOWTHE NIF PROJECT TO PROCEED AS PLANNED

In assessing the scientific and technical readiness of the NIF project, the committee attempted to balance the NIF's potential value against the risk inherent in the extrapolation from the present base of experimental and computational experience.

The science supporting the NIF fusion objectives includes the physics of the imploding capsule and the physics of laser-hohlraum interactions. The issues in these two areas and the requirements for scientific readiness were delineated as milestones in the NOVA Technical Contract (NTC) of 1990, which was based on the point target design at that time. The fulfillment of almost all of the NTC's terms with surrogate targets that precede the current NIF design has led to substantial and encouraging progress in the understanding of both areas, although some issues have not yet been resolved completely.

The NOVA experimental campaign failed to meet its objective of high-convergence implosions (HEP 5). The computational advances of the last 5 years have pinpointed the cause as lack of symmetry in the 10-beam NOVA system. The three-dimensional simulations that successfully describe the NOVA experiments predict that the 192-beam NIF system will have adequate symmetry for high-convergence implosions. This has been confirmed in small capsule experiments. The development of two-dimensional integrated codes during the last 5 years has addressed issues of time-dependent long-wavelength asymmetry.

Since CD-2, the NIF baseline target design has been changed to a gas-filled hohlraum. This change introduced unexpected but seemingly reproducible beam bending and increased backscatter so that several of the HLP 1 to 6 milestones are no longer met and others are, at best, barely met. The cause of this unexpected behavior is thought to be understood, and experiments with one NOVA beam smoothed indicate that beam smoothing will restore the performance to that specified in the NTC. The NIF baseline design has been changed to include beam smoothing, and experiments with all 10 NOVA beams smoothed are planned within the next 6 months to confirm the favorable effects of smoothing. The committee believes that the prognosis for these experiments is sufficiently favorable to justify proceeding with the NIF without delay.

Hohlraum physics issues are absent in the direct-drive approach, which nevertheless imposes more stringent requirements on beam balance and smoothness. Direct-drive experiments are currently being pursued on the 60-beam OMEGA facility and will also be explored with the 192-beam NIF.

The Beamlet laser has validated almost all aspects of the design of the NIF laser. The exceptions are the final focusing optics and the lower damage threshold of the rapidly grown KDP crystals; there are adequate plans for dealing with these two remaining issues. As designed, the NIF laser will operate at a maximum fluence consistent with an optimization of both cost and reliability and projected performance. The NIF laser architecture allows beamline maintenance and repair without disruption of normal operations. The beam-smoothing experiments under way on NOVA have demonstrated that the technology exists to meet the NIF laser performance specifications.

With regard to NIF project management, the committee finds that there is a competent, well-supported project team and a well-aligned project organization. The project has undergone a stringent Title I Review, and an Independent Cost Estimate review has verified the TEC cost estimates. Although the contingency currently provided is unusually tight for such a project, the availability of support from the ICF program during the construction period provides the margin to systems and components necessary for the NIF to the point that a low contingency might be acceptable. The operating budget is defined precisely, but in relatively narrow terms, and is consistent with LLNL's bottom-up analysis. Additional target physics program funds need to be available in order to provide an operating budget comparable to those at other large facilities.

In sum, the committee believes that the NIF can be delivered to specifications within the stated TPC, as augmented by LLNL-projected operating funds, allowing the high-energy-density and ignition experimental programs to proceed; there are no identifiable "show stoppers." The achievement of ignition appears likely, but not guaranteed. The steady scientific and technological progress in ICF during the 6 years since the last National Research Council review, the plausibility of ignition estimates based on the experimental and modeling results and capabilities in hand, and the flexibility of the facility all support the committee's finding that the NIF project is technologically and scientifically ready to proceed as planned with reasonable confidence in the attainment of its objectives.

Appendix A

Meeting Agendas and Attendance

AUGUST 1-2,1996 BECKMAN CENTER, IRVINE CALIFORNIA

Agenda

Thursday, August 1		
0730	Welcome	Steven Koonin, Chair
0745	Administrative Issues	
0815	Charge to the Committee	Robin Staffin, Deputy Assistant Secretary for Research and Development, DOE
	EXECUTIVE SESSION	
0845	Discussion of Committee Balance and Composition	Norman Metzger, Executive Director, Commission on Physical Sciences, Mathematics, and Applications
	BRIEFING SESSION	
1000	Tutorial on Weapon Physics*	Primaries, Bruce Goodwin, LLNL Secondaries, Jas. Mercer-Smith, LANL
1200	Overview on Science-Based Stockpile Stewardship*	Robin Staffin
1330	Overview of Inertial Confinement Fusion Program*	George Miller, Associate Director for National Security, LLNL
1430	ICF Management and Use Plan	David Crandall, Office of Inertial Fusion and National Ignition Facility, DOE
1545	NIF Description and Plans	Jeff Paisner, Program Manager, NIF Project, LLNL
1645	Tutorial on Glass Lasers	Howard Powell, Program Leader for Laser Science and Technology, LLNL
1745	**EXECUTIVE SESSION**	
Friday, August 2		
	BRIEFING SESSION	
0730	Description of Above-Ground Experimentation (AGEX) Program*	Philip Goldstone, Science and Technology Advisor, LANL
0830	Tutorial on Direct Drive	Charles Verdon, Deputy Director, Laboratory for Laser Energetics, University of Rochester
1000	Tutorial on Indirect Drive (partly closed)*	John Lindl, Scientific Director for the ICF Program, LLNL
1115	**EXECUTIVE SESSION**	
1230	**ADJOURN**	

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* Briefing rescheduled to future meeting for reasons of national security.

Attendees

Committee
Steven Koonin
Robert Byer
Robert Conn
Ronald Davidson
Roger Falcone
Hermann Grunder
Arthur Kerman
Marshall Rosenbluth

NRC Staff
Susan Campbell
Mary Gordon
Kevin Hale
Norman Metzger
Sidney Reed (consultant)
Dorothy Zolandz

Department of Energy
Robin Staffin
David Crandall
Chris Keane
Kevin Bieg
Theresa Egan
Doug Drake

Lawrence Livermore National Laboratory
Joe Kilkenny
Michael Campbell
George Miller
Bruce Goodwin
Jeff Paisner
Howard Powell
John Lindl
Roy R. Johnson

Los Alamos National Laboratory
Philip Goldstone
Jas. Mercer-Smith
Melissa Cray

Sandia National Laboratories
Jeff Quintenz
Don Cook

General Atomics
David Baldwin

University of Rochester/Laboratory for Laser Energetics
Robert McCrory
Charles Verdon

Naval Research Laboratory
Stephen Bodner

SEPTEMBER 19-21,1996 LAWRENCE LIVERMORE NATIONAL LABORATORY

Agenda

Thursday, September 19		
	EXECUTIVE SESSION	
0745	Discussion of Committee Balance and Composition	Norman Metzger, Executive Director, Commission on Physical Sciences, Mathematics, and Applications
	BRIEFING SESSION	
0845	Welcome	Steven Koonin, Chair
0900	Weapons Vault Tour **CLOSED**	George Miller, Associate Director for National Security, LLNL
1045	Stockpile Stewardship **CLOSED**	Sid Drell, Deputy Director, Stanford Linear Accelerator Center
1230	Primary Weapons Physics **CLOSED**	Bruce Goodwin, LLNL
1345	Secondary Weapons Physics **CLOSED**	James Mercer-Smith, LANL
1515	Application of High Power Laser to Stockpile Stewardship **CLOSED**	George Miller, LLNL
1630	Weapons AGEX Program **CLOSED**	Philip Goldstone, Science and Technology Advisor, LANL
1745	EXECUTIVE SESSION	Steven Koonin, Chair

Friday, September 20		
	BRIEFING SESSION	
0745	Surveillance Program **CLOSED**	Robert Paulsen, SNL
0845	Personnel Demographics **CLOSED**	All laboratories
0930	Tutorial on Diagnostics	Ray Leeper, SNL
1030	Computational Modeling and Confidence in Ignition **CLOSED**	William Krauser, LANL Steve Haan, LLNL
1200	Lunch and Tour of NOVA and Beamlet	
1415	Status of NAS Technical Contracts for NOVA	Joe Kilkenny, LLNL
1530	Status of NAS Technical Contracts for NOVA, continued **CLOSED**	Melissa Cray, LANL
1630	Status of NAS Technical Contract for OMEGA	Bob McCrory, UR/LLE
1730	EXECUTIVE SESSION	

Saturday, September 21	
0800	EXECUTIVE SESSION
1100	ADJOURN

Attendees

Committee
Steven Koonin
David Arnett
Robert Byer
Robert Conn
Anthony DeMaria
Paul Dimotakis
Jack Dongarra
Roger Falcone
Hermann Grunder
Henry Kendall
Arthur Kerman
Stephen Orszag
Marshall Rosenbluth
George Trilling
J. Pace VanDevender

NRC Staff
Mary Gordon
Norman Metzger
Sidney Reed (consultant)
Ronald Taylor
Dorothy Zolandz

Department of Energy
Kevin Bieg
David Crandall
Doug Drake
Chris Keane
Carol Myers
Scott Samuelson

Lawrence Livermore National Laboratory
Mike Anastasio
Tom Bernay
Bruce Goodwin
Steven W. Hahn
Bruce Hammel
Ted Jaito
Kent Johnson
Roy R. Johnson
Joe Kilkenny
Bob Kauffman
Brian MacGowan George Miller
Thaddeus Orzechowshi
Jeff Paisner
Don Patterson
Steve Pollaine
Howard Powell
Mordecai Rosen
Richard Ward

Los Alamos National Laboratory
Melissa Cray
Juan Fernandez
Philip Goldstone
Nev Hoffman

William Krauser
Jas. Mercer-Smith
Doug Wilson

Sandia National Laboratories
Don Cook
Ray Leeper
Keith Matzen
Robert Paulsen
Jeff Quintenz

University of Rochester/Laboratory for Laser Energetics
Steve Loucks
Robert McCrory
Charles Verdon

Naval Research Laboratory
Stephen Bodner
John Gardner
Steve Obenschain

Other
Sidney Drell
Damon Giovanielli
Bill Hogan
Mike Minsler

OCTOBER 16-17,1996 UNIVERSITY OF ROCHESTER, LABORATORY FOR LASERENERGETICS

Agenda

Wednesday, October 16 — Closed Sessions		
0830	Welcome	S. Koonin, Chair
	EXECUTIVE SESSION	
0845	Committee Executive Session	S. Koonin, Chair
	BRIEFING SESSION	
0915	Weapons Physics Scaling	R. Ward, LLNL
1000	Discussion	
1030	Plans for NIF Weapons Physics Experiments	T. Perry, LLNL
1115	Discussion	
1130	Applications of ICF Laser Technology to the Wxx Life Extension Program	J. Sefcik, LLNL
1145	Discussion	
1300	Hohlraum Symmetry Control, Systematic and Random, Crucial for High-Convergence Implosions	J. Kilkenny, LLNL
1330	Discussion	
1400	Direct Drive Ignition Status and Plans	C. Verdon, UR/LLE
1430	Discussion	
1515	Z-Pinch Tutorial	K. Matzen, SNL
1600	Discussion	
	EXECUTIVE SESSION	
1615	Committee Executive Session	S. Koonin, Chair
1715	Tour of the OMEGA Laser Facility	R. McCrory, UR/LLE
1830	**ADJOURN**	

Thursday, October 17 — Open Sessions		
	BRIEFING SESSION	
0830	ICF Program Planning Overview	D. Crandall, DOE
0845	ICF Program Planning	C. Keane, DOE
0915	Discussion	
1000	NIF Project Planning	S. Samuelson, DOE
1030	Discussion	
1100	NIF Manufacturing Facilitization	H. Powell, LLNL
1130	Discussion	
1315	**EXECUTIVE SESSION**	S. Kooni, Chair
1500	**ADJOURN**	

Attendees

Committee
Steven Koonin
David Arnett
Paul Dimotakis
Jack Dongarra.
Roger Falcone
Hermann Grunder
Henry Kendall
Stephen Orszag
J. Pace VanDevender

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Ronald Taylor
Dorothy Zolandz

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Kevin Bieg
Don Cook
David Crandall
Robert DeWitt
Doug Drake
Chris Keane
Scott Samuelson

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Jeff Atherton
Michael Campbell
Bruce Hammel
Roy R. Johnson
Joe Kilkenny
John Lindl.
George Miller
Thaddeus Orzechowski
Michael Perry
Ted Perry
Howard Powell
Mordecai Rosen
Joe Sefcik
Richard Ward

Los Alamos National Laboratory
John H. Birely
Melissa Cray
Larry Foreman
Jas. Mercer-Smith
Don Wade
Douglas Wilson

Sandia National Laboratories
Don Cook
Keith Matzen
Jeff Quintenz

University of Rochester/Laboratory for Laser Energetics
Steve Loucks
Robert McCrory
P.W. McKenty

J.M. Soures
Charles Verdon

Naval Research Laboratory
Stephen Bodner

NOVEMBER 3-5, 1996 LOS ALAMOS NATIONAL LABORATORY, SANDIA NATIONALLABORATORIES

Agenda

Sunday, November 3 — Los Alamos National Laboratory — Closed Session		
1600	WETF Tour	Arthur Nobile Jr., LANL
1830	**EXECUTIVE SESSION**	
Monday, November 4 — Target Fabrication, LANL — Closed Sessions		
	BRIEFING SESSION	
0800	Welcome	Stephen Younger, LANL
0830	Accelerated Strategic Computing Initiative (ASCI) Program Objectives and Overview	John W. Hopson, LANL
0915	Discussion	
0930	Nuclear Weapons Effects: Test Capability of NIF*	Todd Hoover, DSWA
1000	Discussion	
1045	Target Fabrication for Ignition and Stewardship	Larry R. Foreman, LANL
1145	Discussion	
1300	Target Fabrication Facility (TFF) Introduction	Janet Mercer-Smith, LANL
1315	TFF Tour	
1500	Role of Ignition in Stewardship	Mike Anastasio, LLNL
1530	Discussion	
1600	Ignition Hohlraums: Evolution and Status	Steve Bodner, NRL
1630	Discussion	
1645	Panel on Likelihood of Achieving Ignition on NIF	Mordecai Rosen, LLNL Charles Verdon, LLE Steve Bodner, NRL Keith Matzen, SNL Nelson Hoffman, LANL
1730	**EXECUTIVE SESSION**	
1800	**ADJOURN**	
Tuesday, November 5 — Sandia National Laboratories		
	OPEN SESSION	
0815	Comment from Selected Non-Governmental Organizations	Greg Mello, Los Alamos Study Group Marylia Kelley, Tri-Valley CAREs Daniel Kerlinsky, Physicians for Social Responsibility
0915	Welcome	C. Paul Robinson, SNL
	CLOSED SESSION	
0945	PBFA-Z Introduction	Doug Bloomquist, SNL
1030	PBFA-Z Tour for NRC Committee	

(*table continued on next page*)

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* Briefing withdrawn.

1130	Panel on Relevance of NIF to SBSS—Invitation only	Bernhard Wilde, LANL John M. Pedicini, LANLL Richard Ward, LLNL Dan Patterson, LLNL
1330	**EXECUTIVE SESSION** PBFA-Z Tour for Non-NRC Attendees	
1500	**ADJOURN**	

Attendees, Los Alamos

Committee
Steven Koonin
Robert Byer
Robert Conn
Ronald Davidson
Paul Dimotakis
Jack Dongarra
Roger Falcone
Hermann Grunder
Henry Kendall
Arthur Kerman
Steven Orszag
George Trilling
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H. Carol Myers
Scott Samuelson

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Michael Anastasio
Alan Burnham
E. Michael Campbell
Steven W. Hahn
Bruce A. Hammel
Roy R. Johnson
Robert Kauffman
Joe Kilkenny
John D. Lindl
George H. Miller
Thadeus J. Orzechowski
Dan W. Patterson
Howard T. Powell
Mordecai Rosen
Thomas Thomson

Los Alamos National Laboratory
Melissa Cray
Juan Fernandez
Larry Foreman
Nelson Hoffman
John Hopson
Ross Lemours
Eric Lindeman
Jas. Mercer-Smith
Janet Mercer-Smith
Tom Murphy
Harvey Rose
Kurt Schoenburg
Fritz Swenson
Richard A. Ward
Doug Wilson
Steve Younger

Sandia National Laboratories
Jeff Quintenz
Keith Matzen
Wendland Beezhold
James Lee
William Ballard
Mark Hedemann

University of Rochester/Laboratory for Laser Energetics
Robert McCrory
Charles Verdon

Naval Research Laboratory
Stephen Bodner

Attendees, Sandia National Laboratories

Committee
Steven Koonin
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Howard T. Powell

Los Alamos National Laboratory
Melissa Cray
John M. Pedicini
Bernhard Wilde
Doug Wilson

Sandia National Laboratories
Doug Bloomquist
Chris Deeney
Ray Leeper
Keith Matzen
John Porter
Jeff Quintenz
C. Paul Robinson
Gerry Yonas

University of Rochester/Laboratory for Laser Energetics
Robert McCrory
Charles Verdon

Naval Research Laboratory
Stephen Bodner

Other
Marylia Kelley
Daniel Kerlinsky
Greg Mello

DECEMBER 5-6, 1996 WASHINGTON, D.C.

Agenda

Thursday, December 5

	EXECUTIVE SESSION	
0815	Discussion of findings, report drafting, etc.	
	OPEN SESSION	
1000	Discussion with Thomas Cochran	Natural Resources Defense Council
	EXECUTIVE SESSION	
1030	Committee discussion continued	
1300	Committee discussion continued	
1800	**ADJOURN**	

Friday, December 6

	EXECUTIVE SESSION	
0800	Discussion with Victor H. Reis	Assistant Secretary for Defense Programs, DOE
	Discussion with Robin Staffin	Deputy Assistant Secretary for Research and Development, DOE
1300	Executive Session continued—finish report drafting	
1500	**ADJOURN**	

Attendees

Committee
Steven Koonin
David Arnett
Robert Byer
Robert Conn
Ronald Davidson
Anthony DeMaria
Paul Dimotakis
Jack Dongarra
Roger Falcone
Hermann Grunder
Henry Kendall
Arthur Kerman
Steven Orszag
Marshall Rosenbluth
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J. Pace Vandevender

NRC Staff
Susan Campbell
Mary Gordon
Norman Metzger
Sidney Reed (consultant)
Ronald Taylor
Dorothy Zolandz

Department of Energy
David Crandall
Victor Reis
Robin Staffin

Natural Resources Defense Council
Thomas Cochran

Appendix B

Description of ICF Program and Selected Other Major SBSS Facilities

The maintenance of a safe and reliable U.S. nuclear stockpile over the long term is the mission of the Stockpile Stewardship and Management Program. In the absence of nuclear testing, this program will require an improved understanding of nuclear weapon behavior in the areas of performance, safety, and reliability. Development of this understanding will increasingly depend on computer simulations and analyses benchmarked against past data and new, more comprehensive information obtained from carefully designed laboratory experiments. These experiments will be carried out using a combination of new and existing facilities. New facilities are required to improve access to the physics regimes important for understanding nuclear weapon behavior.

Table B.1 identifies existing and planned Inertial Confinement Fusion program facilities as well as selected other major stockpile stewardship facilities. The list includes those proposed by individual laboratories, many of which have not yet been approved by DOE. Finally, two major stockpile stewardship and management programs, the Accelerated Strategic Computing Initiative (ASCI) and the Advanced Design and Production Technology (ADaPT), are listed for completeness.

A brief description of each of the facilities follows:

- ADaPT is an initiative to develop the tools to integrate the development of weapons components with associated advanced manufacturing and materials processes.
- AHF is a proposed advanced hydrotest facility using new and developing accelerator technology that would provide time-resolved images of the implosion of a weapon primary from several different angles of view.
- APT is a proposed alternative for producing tritium using an accelerator instead of a nuclear reactor.
- ASCI is an initiative to create the leading-edge computational modeling and simulation capabilities that are essential for maintaining the safety, reliability, and performance of the nuclear stockpile.
- ATLAS is a new pulsed-power facility with a 36-MJ capacitor bank that will provide an order-of-magnitude increase in dynamical pressure over that provided by PEGASUS.
- CFF is located at LLNL Site 300 to provide a continuing capability for testing the high-explosive component of a nuclear weapon.
- DARHT, a hydrotesting facility under construction at LANL, provides two views of an imploded pit through the use of two electron accelerators placed at right angles to each other.
- HEAF is an experimental facility at LANL that assesses detonators and the initiation and burning of high explosives.
- HEPPF is a proposed next-generation large-explosive experimental facility at the Nevada Test Site for experimental physics studies related to weapons secondary at shock pressures and velocities approaching actual weapon conditions.

- LANSCE is a defense programs neutron science center. The LAMPF complex at LANL has been converted to LANSCE to support general defense program objectives, particularly radiographic and neutron studies.
- LPSS is a proposed 1-MW cold neutron source at LANL for the study advanced materials.
- NIF is a 192-beam, 1.8-MJ glass laser facility for conducting high-energy-density experiments (temperatures up to 600 eV) and demonstrating inertial fusion ignition in the laboratory.
- NIKE is a 4-kJ krypton fluoride (FrF) gas laser at NRL for studying direct-drive inertial fusion issues and other related phenomena.
- NOVA is a 10-beam (~40-kJ) glass laser facility at LLNL for conducting indirect drive inertial fusion experiments and weapons-related high-energy-density science experiments.
- OMEGA is a 60-beam (45-kJ) glass laser facility at the University of Rochester for conducting direct-drive inertial fusion experiments.
- PBFA is a fast-pulsed accelerator (~50 ns) at Sandia National Laboratories; PBFA II, PBFA X, and PBFA Z are modifications to the accelerator to conduct light ion inertial fusion experiments, light ion extraction experiments, and z-pinch experiments, respectively.
- PEGASUS is a 4.3-MJ capacitor bank at LANL with a slow (microseconds) direct drive for hydrodynamic studies with an experimental volume of I cubic centimeter.
- PHERMEX is a dynamic radiography facility located at LANL.
- PROCYON is a 15-MJ, high-explosive, pulsed-power system at LANL providing 2-to 6-microsecond drive. It has been used for direct-drive plasma implosions to produce soft x-rays for weapon physics experiments.
- SABRE is a positive-polarity-induction linear accelerator located at SNL. SABRE uses an extraction ion diode and is used mainly for studies of light ion beam generation, transport, and focusing.
- SATURN is a fast-pulsed accelerator at SNL that can produce a 600-kJ radiation source from a 4-MJ Marx capacitor bank. The source is used for studies of nuclear weapons effects and hohlraums (up to 100 eV).
- SPSS is a capability at LANSCE to provide moderated (low-energy) neutrons with wavelengths comparable to atomic physics dimensions to address primary physics issues.
- TRIDENT is a multipurpose Nd:glass laser facility at LANL that supports inertial fusion, weapons physics, and other experiments and instrument development. Trident has two main beams with 100 J per beam in a 100-ps pulse with a third beam used for backlighting. The TRIDENT Upgrade is proposed to produce several kilojoules.
- WETF is a facility at LANL to investigate tritium technology for weapons applications.
- X-1 is a proposed advanced z-pinch radiation source producing 8 to 10 MJ of soft x-rays.

Table B.1 Existing and Planned Inertial Confinement Fusion Program Facilities

Existing Facilities	Approved Facilities[a]	Proposed Facilities[b]
Lasers		
NOVA	National Ignition Facility (NIF)	TRIDENT Upgrade
OMEGA		
NIKE		
TRIDENT		
Pulsed Power		
PBFA II (PBFA X, PBFA Z)	ATLAS	X-1
SATURN		ATLAS—$34 million
PEGASUS		
PROCYON		
SABRE		
Neutron Radiographic		
Los Alamos Neutron Scattering Center (LANSCE)	Short-Pulse Spallation Source (SPSS)	Long-Pulse Spallation Source (LPSS)
Hydrodynamics		
Pulsed High-Energy Radiographic Machine Emitting X-Rays (PHERMEX)	Dual-Axis Radiographic Hydrodynamic Testing Facility (DARHT)	Advanced Hydrotest Facility (AHF)
Flash X-Ray (FXR)—$81 million		
Materials		
Weapon Engineering Tritium Facility (WEFT)		Accelerator Production of Tritium (APT)
Explosive		
High Explosives Application Facility (HEAF)		High Explosive Pulsed Power Facility at NTS (HEPPF)
Test		
Contained Firing Facility (CFF)		
Computing		
Accelerated Strategic Computing Initiative (ASCI)		
Manufacturing		
Advanced Design and Production Technology (ADaPT)		

[a] Includes partially funded facilities.

[b] Includes laboratory-proposed facilities not yet approved by DOE.

Appendix C

Biographical Information

Steven E. Koonin (Chair) is vice president and provost and a professor of physics at the California Institute of Technology. His areas of expertise include theoretical nuclear physics and computational physics; current research interests include nuclear structure and reaction models and quantum computing. He has served as a consultant for various national laboratories, including Lawrence Berkeley, Lawrence Livermore, Los Alamos, and Oak Ridge. He chaired the National Research Council's (NRC's) 1990 review of the Inertial Confinement Fusion (ICF) program, served on the Department of Energy's (DOE's) Inertial Confinement Fusion Advisory Committee (ICFAC), and participated in a review of Science Based Stockpile Stewardship as part of the JASON group. He is a fellow of the American Physical Society, the American Academy of Arts and Sciences, and the American Association for the Advancement of Science.

W. David Arnett is a Regents' Professor of Astrophysics at the University of Arizona. His research interests include nuclear, relativistic, and computational astrophysics. His previous positions include terms at the University of Chicago and as a Distinguished Professor at the Enrico Fermi Institute. He is a fellow of the American Physical Society and is a member of the International Astronomical Union and the American Academy of Arts and Sciences. He has recently participated in experiments using the NOVA laser facility at Lawrence Livermore. He is a member of the National Academy of Sciences.

Robert L. Byer is a professor of applied physics and director of the Center for Nonlinear Optical Materials at Stanford University. He previously served as Stanford's dean of engineering. His research expertise includes diode-pumped solid-state lasers, nonlinear optics, nonlinear materials, and laser remote sensing. He serves on the Director's Advisory Committee at Lawrence Livermore National Laboratory and has consulted for its laser directorate. He served as a consultant to the ICFAC in its review of the National Ignition Facility laser design. He is a fellow of the Institute of Electrical and Electronics Engineers, the Optical Society of America, and the American Physical Society, and is past president of the IEEE Lasers and Electrooptics Society. He is a member of the National Academy of Engineering.

Robert W. Conn is dean of engineering and Walter J. Zable Professor of Engineering and Applied Science at the University of California, San Diego. His experience in fusion physics and engineering, and in plasma and materials technology, includes specific expertise in the dynamics of fusion burning plasmas, the interaction of plasma with material surfaces, and fusion reactor design. He has served on numerous DOE magnetic fusion advisory committees, as well as on the NRC's 1990 review of ICF. He is a fellow of the American Nuclear Society and the American Physical Society. He is a member of the National Academy of Engineering.

Ronald C. Davidson is a professor of astrophysical sciences at Princeton University. He headed the university's Physics Laboratory from 1991 through 1996. His previous positions include that of assistant director for applied plasma physics in the Office of Fusion Energy, DOE, and 10 years as director of the Massachusetts Institute of Technology Plasma Fusion Center. His research interests include plasma turbulence, nonlinear plasma theory, nonneutral plasmas, and intense charged particle beams. He has served on numerous national and international review committees, including the 1986 and 1990 NRC reviews of the ICF program, and on the DOE ICFAC. He is a fellow of the American Physical Society.

Anthony J. DeMaria is chairman and president of DcMaria Electrooptics Systems, Inc. and a research professor at the University of Connecticut Photonics Research Center. His previous experience includes the positions of assistant director of research for electronics and photonic technologies, and acting assistant director of research for information systems and technology, at United Technologies. His expertise in applied and laser physics includes experience in utilization of laser devices, interaction of elastic waves with coherent light radiation, gas laser research and applications, and acoustic-and electrooptics. He served on the 1990 NRC review of the ICF program, and on the DOE ICFAC. He is a fellow of the IEEE, and past editor of the IEEE *Journal of Quantum Electronics*, a fellow and past president of the Optical Society of America, and a fellow of the American Physical Society. He is a member of the National Academy of Engineering.

Paul E. Dimotakis is the John K. Northrop Professor of Aeronautics and a professor of applied physics at the California Institute of Technology. His research focuses on investigations of turbulent-flow phenomena, with an emphasis on turbulent transport and mixing in liquid-and gas-phase, chemically reacting as well as nonreacting flows, and combustion. He has consulted for the Lawrence Livermore National Laboratory in the area of turbulence and turbulent mixing and has participated in experiments at the NOVA laser facility at Lawrence Livermore. He is a fellow of the American Physical Society.

Jack J. Dongarra holds a joint appointment as Distinguished Professor of Computer Science at the University of Tennessee and as Distinguished Scientist in the Mathematical Sciences Section at Oak Ridge National Laboratory. He was formerly the scientific director of the Advanced Computational Research Facility at Argonne National Laboratory. His expertise includes numerical algorithms in linear algebra, parallel computing, use of advanced computer architectures, programming methodology, tools for parallel computers, and high-quality mathematical software. He is a fellow of the American Association for the Advancement of Science.

Roger W. Falcone is professor and chair of the Department of Physics at the University of California at Berkeley. His recent research includes topics in laser interaction with solids, gases, and plasmas; atomic physics; and x-ray scattering. Dr. Falcone has served on numerous scientific advisory committees, including several for the National Science Foundation involving a science and technology center, the LIGO project at MIT and Caltech, and a visiting committee at NSF; a review committee for the Max Planck Institute in Garching; and advisory committees for Lawrence Livermore National Laboratory. He has served on numerous national and international advisory committees for scientific societies. Throughout his career he has consulted for several laser and electrooptics companies and has consulted with Lawrence Livermore National Laboratory in the areas of laser interaction with matter and other areas of physics in the laser and physics divisions. He has received partial support from DOE for several research projects at Berkeley through LLNL. He is a recipient of an NSF Presidential Young Investigator Award and is a fellow of the American Physical Society and the Optical Society of America.

Hermann A. Grunder is the director of the Thomas Jefferson National Accelerator Facility, the DOE's newest laboratory for nuclear physics research in Newport News, Virginia. Before coming to Jefferson Laboratory in May 1985, he served as deputy director of general sciences at Lawrence Berkeley Laboratory. Experienced in the design, construction, and operation of accelerators and neutral beam injectors, Dr. Grunder has also managed large facilities through construction and operations. Dr. Grunder is a fellow of the American Physical Society, is division councilor of the Division of Physics of Beams, and has served on a number of professional and review committees such as the DOE Joint Coordinating Committee on the Fundamental Properties of Matter, the Relativistic Heavy Ion Collider Policy Committee, and the National Institute of Standards and Technology Panel for Radiation Research.

Henry W. Kendall is the J.A. Stratton Professor of Physics at the Massachusetts Institute of Technology. He is recognized for his research in high-energy physics, including high-energy experimental physics and nucleon structure. He is a founding member of the Union of Concerned Scientists (UCS), an organization whose missions include advocacy of U.S. policies and international agreements that control nuclear weapons proliferation and lower the risk of nuclear war. He has served as chairman of the UCS since 1973. He has held various advisory positions, including service on the JASON group and on the Galvin Committee review of the DOE laboratories. He is an advisor to the World Bank and is the organizer and chairman of the bank's Panel on the Genetic Engineering of Crops. He is on the board of trustees of the Woods Hole Oceanographic Institution as well as of the National Religious Partnership for the Environment. He is the recipient of numerous prizes and awards, including the 1990 Nobel Prize for physics. He is a fellow of the American Association for the Advancement of Science and the American Physical Society. He is a member of the National Academy of Sciences.

Arthur K. Kerman is a professor of physics at the Massachusetts Institute of Technology. His research interests in theoretical nuclear physics include nuclear QCD-relativistic heavy-ion physics, nuclear reactions, and laser accelerators. Over the course of 30 years, he has had various long-standing consulting relationships with Argonne, Brookhaven, Lawrence Berkeley, Lawrence Livermore, Los Alamos, and Oak Ridge national laboratories, as well as with several private companies and the National Bureau of Standards (now NIST). He currently has active consulting relationships with LLNL and LANL. He has similarly served on numerous professional committees for DOE, the National Science Foundation, Stanford University, the University of California, and the White House. He currently serves on the Director's Advisory Committee of LLNL, the Physics and Space Technology Advisory Committee at LLNL, the Relativistic Heavy Ion Collider Policy Committee at Brookhaven, the Physics Division Advisory Committee at LANL, and the Theory Advisory Committee at LANL. He was a member of the DOE ICFAC. He is a fellow of the American Physical Society and the American Academy of Arts and Sciences.

Steven A. Orszag is the Forrest G. Hamrick '31 Professor of Engineering and Professor of Applied and Computational Mathematics at Princeton University. He is well recognized for his expertise in fluid dynamics and applied mathematics, and is co-author with Carl Bender of the widely used textbook *Advanced Mathematical Methods for Scientists and Engineers*. He is the recipient of numerous awards, including the American Physical Society's Otto Laporte Award for fluid dynamics, the American Institute of Aeronautics and Astronautics Fluid and Plasma Dynamics Award, and the G.I. Taylor Medal. He is a fellow of the American Physical Society.

Marshall N. Rosenbluth is a professor of physics Emeritus at the University of California at San Diego. His research interest is the theoretical physics of plasmas. He was a nuclear weapons designer at Los Alamos National Laboratory early in his career (1950–1956). He consults primarily as a member of the Joint Central Team of the International Thermonuclear Experimental Reactor (ITER), which is funded by the DOE Office of Fusion Energy Science (the ICF program is independent of DOE OFES), and also consults at General Atomics. His committee service includes membership on committees concerned with international security and arms control, such as the JASON group, and the National Research Council's Committee on International Security and Arms Control. He served on both the 1986 and 1990 NRC reviews of the ICF program, as well as on the DOE ICFAC. He is a winner of the Fermi Prize. He is a member of the National Academy of Sciences.

George H. Trilling is Professor Emeritus at the University of California and the Lawrence Berkeley National Laboratory. His expertise is in high-energy physics. He has served on numerous advisory groups, including the High Energy Physics Advisory Panel of the DOE and committees for Fermilab, Argonne National Laboratoryl Brookhaven National Laboratory, and the Stanford Linear Accelerator Center. He is a fellow of the American Physical Society and the American Academy of Arts and Sciences. He is a member of the National Academy of Sciences.

J. Pace VanDevender is the founder of Prosperity Institute, a firm dealing in the study and applications of human factors. He previously held positions at Sandia National Laboratories, where he headed the pulsed-power program from 1984 to 1993. His responsibilities in that position included pulsed-power research and development, inertial confinement fusion, nuclear weapons effects simulation, and directed energy weapon research and development. He is a member of the Naval Studies Board of the National Research Council and has served on the Carrier 21 Study, the Mine Warfare Study, and the study on implications of advancing technology for Navy warfare in the twenty-first century. In addition, he has been a member of numerous advisory boards, including the Advance Photon Source at Argonne National Laboratory, the Compact Ignition Tokomak of Princeton Plasma Physics Laboratory, the Directed Energy Advisory Board of the Strategic Defense Initiative, and the Defense Sciences Advisory Board of Los Alamos National Laboratory. He is a fellow of the American Physical Society and a senior member of the Institute of Electrical and Electronics Engineers. He was awarded the Department of Energy's Lawrence Award for Physics in 1991.

Appendix D

Acronyms and Abbreviations

AGEX	Above-ground experimentation
ASCI	Accelerated Strategic Computing Initiative
CD-1, etc.	Critical Decision 1, etc.
DOD	Department of Defense
DOE	Department of Energy
DP	Defense Programs (DOE)
DT	Deuterium-tritium
HEP	Hydrodynamic equivalent physics
HLP	Hohlraum laser physics
ICE	Independent cost estimate
ICF	Inertial confinement fusion
ICFAC	Inertial Confinement Fusion Advisory Committee
IFE	Inertial fusion energy
ISI	Induced spatial incoherence
KDP	Potassium dihydrogen phosphate
KPP	Kinoform phase plate
LANL	Los Alamos National Laboratory
LLE	Laboratory for Laser Energetics (University of Rochester)
LLNL	Lawrence Livermore National Laboratory
MO	Master oscillator
NIF	National Ignition Facility
NIKE	Not an acronym; name of existing laser facility at Naval Research Laboratory
NOVA	Not an acronym; name of existing laser facility at Lawrence Livermore National Laboratory
NRC	National Research Council
NRL	Naval Research Laboratory
NTC	NOVA Technical Contract
OMEGA	Not an acronym; name of existing laser facility at University of Rochester Laboratory for Laser Energetics
RPPs	Random phase plates
SBS	Stimulated Brillouin Scattering
SBSS	Science Based Stockpile Stewardship
SNL	Sandia National Laboratories
SRS	Stimulated Raman scattering
SSD	Smoothing by spectral dispersion
TEC	Total estimated cost
TPC	Total project cost