Soaring Cost, Shrinking Performance

Status of the National Ignition Facility

A Report for Tri-Valley CAREs

by Dr. Robert Civiak

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ON THE COVER: The cover photograph shows the inside of the target chamber of the NIF during its installation. The many holes are ports for the laser beams to enter the chamber and for mounting diagnostic equipment to collect data from experiments.

Photo credit: Lawrence Livermore National Laboratory

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Tri-Valley CAREs (Communities Against a Radioactive Environment) is a Livermore, California-based 501(c)(3) nonprofit organization dedicated to increasing public knowledge of the relationship between peace, social justice and the environment, with a special focus on nuclear weapons and nuclear waste.

Tri-Valley CAREs

Communities **A**gainst a **R**adioactive **E**nvironment

2582 Old First Street, Livermore, CA 94550
(925) 443-7148
http://www.igc.org/tvc/

About the Author

Bob Civiak has been doing research and analysis in nuclear weapons policy and related areas for more than 20 years. He received a Ph.D. in physics from the University of Pittsburgh in 1974. From 1978 through 1988 he was a Specialist in Energy Technology and Section Head in the Science Policy Research Division of the Congressional Research Service (CRS) at the Library of Congress. During the spring and summer of 1988 he was a Visiting Scientist at Lawrence Livermore National Laboratory. From November 1988 through August 1999 he was a Program and Budget Examiner with the Office of Management and Budget (OMB) in the Executive Office of the President. At OMB his primary responsibilities included oversight of the national security activities of the Department of Energy, including the Stockpile Stewardship Program. He currently resides in Lebanon, New Hampshire, where he continues to do research and policy analysis on nuclear weapons and arms control issues as an independent consultant. His previous work for Tri-Valley CAREs includes a report titled, “Managing the U.S. Nuclear Weapons Stockpile: A Comparison of 5 Strategies” which was released in July 2000.

Acknowledgments

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SOARING COST, SHRINKING PERFORMANCE: STATUS OF THE NATIONAL IGNITION FACILITY

Executive Summary

The Department of Energy (DOE) is keeping the full cost of its largest construction project, the National Ignition Facility (NIF), from Congress and the U.S. taxpayers. Over the life of the facility, it is likely to cost more than $30 billion. Even at this inflated price, the NIF is exceedingly unlikely to meet its performance objectives. Moreover, whether it does or does not, the NIF would be of limited use for its primary mission, which is to assist the Department of Energy in maintaining U.S. nuclear weapons.

We have documented a continuing pattern of increasing cost and declining performance expectations for the NIF, which is under construction at Lawrence Livermore National Laboratory (LLNL). From the time Congress first authorized the NIF Project in 1995, DOE has increased its estimate of the cost to build the facility from $1.1 billion to $3.4 billion and has delayed the projected date for completing construction of the NIF from 2002 to 2008.

DOE still significantly understates the likely cost of construction. One way it does that is by not including all project-related costs in its estimate. A full accounting of the costs to complete construction of the NIF *on DOE's schedule in 2008* comes to $5.0 billion. This estimate assumes there will be no more problems with the NIF that would result in additional cost overruns or schedule delays. On the contrary, there is significant potential for future problems and delays. This report identifies a number of technical challenges that DOE must still resolve to meet the design requirements for the NIF. Difficulties in resolving any one of those technical problems could delay the NIF Project by one or more years and increase its cost significantly.

A full accounting of the costs to complete construction of the NIF on DOE's schedule in 2008 comes to $5.0 billion. A full accounting of the cost to build and operate the NIF for 30 years, as DOE plans, comes to $32.4 billion.

Furthermore, construction costs are just the tip of the iceberg. To throw the switch and operate the facility would cost much more. DOE has dramatically underestimated the operating costs for the NIF. The Department's estimate excludes overhead costs and much of the cost of the experiments that DOE plans to carry out at the facility. A full accounting of the cost to build and operate the NIF for 30 years, as DOE plans, comes to $32.4 billion. That is more than six times what DOE estimated the life-cycle costs would be when Congress first approved the NIF.

The NIF is intended to produce, for the first time in a laboratory setting, conditions of matter close to those that exist at the center of stars and in detonating nuclear weapons. To accomplish this, it would focus 192 laser beams, with 45 times more energy than any previous laser system, on a tiny capsule of nuclear fuel. If NIF achieves its ultimate goal, the lasers will compress the nuclear fuel until it “ignites” to release about fifteen times more energy than was added.

Despite its skyrocketing costs, the NIF Project is not assured of meeting its goals. It will be many years before DOE will know whether it can focus 192 beams at full energy and pulse length, with the requisite beam quality, simultaneously on a target. DOE does not plan to demonstrate that individual laser beams can reach even as much as 75 percent of their full energy and focus as much as 75 percent of that on targets until 2006. The ability of the laser system to reach full energy on targets will remain uncertain considerably beyond that date. Moreover, the materials currently used in key components of the laser cannot withstand damage from the intense energy of the laser light at full energy (i.e. high light fluence) for more than a few shots. DOE is studying this problem, but is far from solving it. If DOE cannot significantly improve the damage resistance of materials, scientists will be unable to perform nearly as many full energy shots on the NIF as previously projected.

The current DOE estimate still excludes $1.332 billion in project-related spending, which should be counted in the cost of the building the NIF. In addition, proposed enhancements to NIF could add $180 million to the cost before the scheduled Project completion in 2008.

Combining the full projected cost of building and operating the NIF, with its likely limited operation at maximum energy, we calculate that the output from the NIF laser will be only one-ninth the amount per dollar spent that DOE anticipated as recently as last year. This represents a dramatic decline in the projected return on the taxpayer’s investment.

Furthermore, DOE might not meet its primary scientific goal of ignition. DOE has theoretical designs for fusion targets, which it believes might ignite. However, they are idealized designs with characteristics, such as near perfect smoothness, which may well prevent DOE from ever fabricating them. After years of effort, DOE has not yet been able to fabricate a single target that meets the specifications it believes are necessary for ignition with the NIF.

The only logical reason for DOE to continue to spend vast sums on a project as dubious as the NIF is to preserve jobs and weapons design capabilities for nuclear weapons scientists at Livermore Laboratory. This is a questionable activity, whose staggering costs may drain funds from more crucial activities.

The soaring costs and shrinking performance of the NIF is summarized below.

DOE Still Underestimates the Cost of Building the NIF

In August 2000, DOE increased its estimate of the cost of building the NIF from $1.198 billion to $3.448 billion. A little more than $1 billion of the increase resulted from adding four years to the construction schedule. The rest appeared because DOE acknowledged for the first time that it would spend $1.2 billion on project-related activities, which the Department did not previously count as part of the cost of the NIF.

The current DOE estimate still excludes $1.332 billion in project-related spending, which should be counted in the cost of the building the NIF. In addition, proposed enhancements to NIF could add $180 million to the cost before the scheduled Project completion in 2008. Adding those numbers to DOE's August 2000 cost estimate brings the total cost to build and commission the NIF on schedule in 2008 to $4.960 billion. These additional costs are summarized in Table ES-1 and explained in the full report.

Table ES-1

FULL ACCOUNTING OF THE COST TO BUILD NIF
(in billions of dollars)

CATEGORY	COST
DOE August 2000 baseline cost estimate	$3.448
PROJECT RELATED SPENDING EXCLUDED FROM DOE'S COST ESTIMATE	
Target Design and Fabrication	0.491
NIF Program Facilities and Infrastructure	0.400
NIF Support From Other Laboratories	0.136
Target Diagnostics and Instrumentation	0.175
Cryogenic Target Positioning System	0.100
Items Shifted to the Operating Budget in 1997	0.030
SUBTOTAL	$1.332
PROJECT ENHANCEMENTS EXPECTED BEFORE 2008	
Increase Number of Laser Slabs to Eighteen per Beam	0.060
Enhance Use of Other Inertial Fusion Facilities	0.120
SUBTOTAL	0.180
TOTAL	$4.960 billion

Additional Delays and Cost Increases are Likely

The above cost estimates assume there will be no more problems with the NIF Project that would result in additional cost overruns or schedule delays. There is, however, significant potential for future problems and delay. The NIF is one of the most complex, technically challenging projects ever undertaken by the Department of Energy. Such projects by their very nature are highly subject to delays and cost overruns. The U.S. General Accounting Office reviewed DOE's record for completing major projects on time and on budget in 1996 and found:

> From 1980 through 1996, the Department of Energy (DOE) conducted 80 projects that it designated as major system acquisitions. DOE has completed 15 of these projects — most of them behind schedule and over budget. Three of the completed projects have yet to be used for their intended purpose. Thirty-one other projects were terminated before completion, after expenditures of more than $10 billion. The remaining 34 projects are ongoing. Cost overruns and "schedule slippages" continue to plague many of these ongoing projects.[1]

DOE's past record almost guarantees there will be more schedule delays and cost overruns.

DOE must still resolve several technical hurdles before it can complete and operate the NIF according to its design requirements. Problems in resolving any one of them could lead to additional delays and cost increases. Unresolved technical issues include:

- DOE will not know if the laser system can meet its energy, power, and focusing requirements for many years.

- Using current materials, damage to key optical components of the NIF during operation would severely limit the number of experiments per year at full energy.
- DOE has yet to finish and polish “KDP” and “DKDP” crystals sufficiently to meet the required specifications of smoothness and orientation.[2]
- DOE has yet to fabricate fusion targets that meet the specifications required for ignition.
- It will be difficult for DOE to assemble the laser to the required standard of cleanliness in the cramped and dirty environment of the existing building.
- DOE must build and maintain near flawless control systems and software to monitor and control 60,000 sensors and moving parts for every laser shot.
- DOE’s glass vendors have not demonstrated that they can provide 3,000 high purity neodynium glass-slabs that meet all specifications in a timely manner.

DOE has already delayed full operation of the 192-beam NIF by six years from its initial schedule and by nearly four years from the schedule sent to Congress in 1997. One must account for this delay to fairly compare the earlier cost estimates with current estimates. There is a financial cost to the delay, because the Government’s investment in building the facility sits idle for a longer time. Since the Government is still paying interest on a sizable national debt, the Government’s investment in an expensive facility, such as the NIF, should reflect the interest during construction. This is called imputed interest.

The practice of adding interest during construction to the estimated cost of a capital project is normal practice in the private sector. A company must calculate its full investment in a facility, including interest, in order to determine the return on its investment needed to profit from building the facility. Thus, even though the U.S. Government will not sell the products of the NIF, it is useful to calculate the full investment in the facility in order to weigh the value of its output against its full cost.

When interest at the rate of 10-year Treasury bonds is applied to our estimate of the total cost of completing the NIF Project on DOE’s schedule in 2008, it increases to $7.081 billion. Furthermore, each year of delay would add $325 million in direct costs and $400 million in imputed interest to the cost. Hence, if NIF is delayed only one additional year, the full cost to build the facility, including imputed interest, would increase to $7.8 billion. That is three times the comparable 1997 cost estimate and more than seven times the $1.1 billion cost estimate from the Conceptual Design, which DOE used to gain Congressional approval of the NIF in 1995.

DOE Underestimates the Operating Costs for the NIF

DOE estimates that the cost to operate NIF will be $145 million per year in 2001 dollars. With escalation to the years in which the money will be spent, DOE's estimate of operating costs equates to $8.7 billion over its projected 30-year life for the NIF. However, that figure is only a fraction of the real cost, because it excludes several categories of expenses that are directly related to operating the NIF. We estimate it would cost DOE $440 million annually in 2001 dollars to operate the NIF. Table ES-3 summarizes these annual costs.

Table ES-3

ANNUAL OPERATING COSTS FOR THE NIF

(2001 dollars in millions)

CATEGORY	COST
DOE Estimate per Construction Project Data Sheet	145
Full Cost of DOE Programs' Experiments on the NIF	98
Diagnostic Equipment for Program Users	10
Full Cost of Maintaining the Final Optics Assembly	40
Laboratory Overhead	147
TOTAL	$440 million

If the annual operating cost of $440 million is multiplied by 30 years, the result is $13.2 billion. That figure, however, is in 2001 dollars. If the annual operating cost is adjusted for inflation (at a rate of 3 percent per year) to the years in which the money will be spent, our estimate of operating costs over DOE's projected 30-year life for the NIF comes to $26.5 billion. In total, including the initial cost of construction, operating costs during the construction period and for the next 30 years, and the cost of future upgrades to the facility, we estimate it will cost $32.4 billion to build and operate the NIF. That is more than six times what DOE estimated the life-cycle costs would be when the Project was first approved.

The $32.4 billion figure in the previous paragraph is expressed in "as-spent" dollars. That is dollars that are valued in the year in which they have been or are projected to be expended. That method provides the most intuitive estimate of what total spending on a project will be. It is useful, however to also calculate the decision cost in today's dollars of proceeding with or canceling the NIF. To do that, one should look only at the future costs (from 2002 forward) and should discount those costs to the present.[3] Using a discount rate of 6 percent per year, which is appropriate for Government spending, our estimate of the discounted future cost of building and operating the NIF is $9.9 billion (2001 dollars). This means that canceling the NIF this year would save $9.9 billion in 2001 dollars.

Conclusions and Recommendations

We have documented a continuing pattern of increasing cost and declining performance expectations for the National Ignition Facility. In addition, the NIF Project still faces several challenging technical problems, which DOE has not yet resolved. One or more of those problems could cause additional schedule delays and cost increases. If they are not resolved, the NIF laser may never operate at its design energy or may do so only for a very restricted number of experiments.

Furthermore, the NIF Project may not meet its most important scientific goal — ignition of fusion targets.

According to DOE, NIF is essential to its “Stockpile Stewardship” program. Stockpile Stewardship is what DOE calls its efforts to maintain the safety and reliability of the U.S. nuclear weapons stockpile. In fact, as we have shown in an earlier report,[4] the NIF is not needed for Stockpile Stewardship. Rather, its staggering cost may drain funds from more crucial activities.

We Recommend That:

Because of the dramatic decrease in the expected return on the Government’s investment in the NIF, continuing to fund the Project is no longer justified, if in fact it ever was. The NIF Project should be cancelled.

Every taxpayer with an interest in cost-effective management of the U.S. nuclear weapons stockpile and Government efficiency should work to cancel the NIF Project as soon as possible.

As preliminary steps, the Office of Management and Budget and the General Accounting Office should use this report as a reference in doing their own analyses of the full life-cycle cost of the NIF. In addition, Congress should commission a fully independent, technical and cost review of the NIF. These reviews should be the basis for congressional hearings examining the full cost of building, commissioning, and operating the NIF; examining whether DOE can meet its performance goals; and determining whether DOE is justified in continuing the Project.

Notes

1 U.S. General Accounting Office. Department of Energy: Opportunity to Improve Management of Major System Acquisitions. Chapter Report. 11/26/96, GAO/RCED-97-17.

2 KDP stands for “Potassium Dihydrogen Phosphate.” DKDP is potassium dihydrogen phosphate in which the hydrogen atoms have been replaced by deuterium (an isotope of hydrogen). Together, crystals of these two materials can convert light passing through them to three times its incoming frequency. Such frequency tripling is essential for proper operation of the NIF.

3 Discounting is the standard method of accounting for the time value of money. It recognizes that considerably less than $1 million is needed today to pay a $1 million dollar liability that will not come due for thirty years. As little as $174 thousand dollars invested in a 30-year bond, which pays six percent interest, would provide $1 million to pay a bill that comes due 30 years from now. In the case of the NIF, it is proper to discount the life cycle cost to the present, using a six percent discount rate, to determine the true cost in today’s dollars of continuing the project to its completion.

4 Civiak, Robert. *Managing the U.S. Nuclear Weapons Stockpile: A Comparison of 5 Strategies.* A Report for Tri-Valley CAREs. July 2000.

Introduction

This report documents a continuing pattern of increasing cost and declining performance expectations for the National Ignition Facility (NIF). The National Ignition Facility is the largest, most complex project undertaken by the Department of Energy (DOE) since cancellation of the $12 billion Superconducting Super Collider (SSC) in 1993. Under construction at Lawrence Livermore National Laboratory (LLNL), the NIF is scheduled for completion in 2008 at a cost DOE estimates to be $3.4 billion. However, DOE does not include all of the costs related to the Project in its estimate. A full accounting for the cost to build NIF and commission it for operation in 2008 comes to $5.0 billion.

That cost estimate assumes there will be no more problems with the NIF Project that could result in cost overruns or schedule delays. On the contrary, there is significant potential for future problems and delays. We have identified a number of critical technical challenges, any one of which could require significantly more time to resolve than is currently scheduled.

Furthermore, construction costs are just the tip of the iceberg. To throw the switch and operate the facility would cost much more. DOE has dramatically underestimated the operating costs for the NIF. The Department's estimate excludes overhead costs and it excludes much of the cost of programmatic activities that DOE plans to carry out at the facility. When these and other appropriate costs are added to the DOE estimate, a full accounting of the cost to build and operate the NIF for 30 years, as DOE plans, comes to $32.4 billion. That is more than six times what DOE estimated the life-cycle costs would be when the project was first approved.

A full accounting for the cost to build NIF and commission it for operation in 2008 comes to $5.0 billion. A full accounting of the cost to build and operate the NIF for 30 years, as DOE plans, comes to $32.4 billion.

The NIF is intended to produce, for the first time in a laboratory setting, conditions of matter close to those that exist at the center of stars and in detonating nuclear weapons. To accomplish this, it would focus 192 laser beams, with 45 times more energy than any previous laser system, on a tiny capsule containing nuclear fuel. The NIF lasers are to be housed in a stadium-sized (200 by 85 meters) building at the Livermore Lab. If NIF achieves its ultimate goal, the lasers will compress the nuclear fuel until it "ignites" to release about fifteen times more energy than was added. This ignition would simulate conditions in an exploding thermonuclear weapon.

According to DOE and LLNL officials, NIF is essential to DOE's "Stockpile Stewardship" program, which is what DOE calls its efforts to maintain the safety and reliability of the U.S. nuclear weapons stockpile. However, the NIF is not needed for Stockpile Stewardship. Rather, its staggering cost may drain funds from more crucial activities.

Compounding the issue of high cost, the NIF is unlikely to meet all of its performance goals. The Project may not meet its most important scientific goal, which is ignition of fusion targets. After many years of work, the Department of Energy has not been able to make the type of fusion targets it needs to achieve ignition. In addition, DOE still faces challenging materials problems that limit the operating energy of the laser. If they are not resolved, the output of the NIF laser per dollar spent could be as little as one-ninth what DOE anticipated as recently as last year.

Mission of the NIF

When the Project began, the Department of Energy justified building NIF for its potential to contribute to several of DOE's broad missions. According to the 1994 Conceptual Design Report (CDR),[1] which established the basis for moving ahead with NIF:

> The mission of the National Ignition Facility (NIF) Project is to provide an above ground experimental facility capable of achieving fusion ignition for maintaining nuclear competence and weapons effects simulation, furthering the development of inertial fusion energy, and supporting the development of high energy-density physics.

In discussing the benefits of the NIF, the CDR went on to describe its benefits for science and technology, industrial competitiveness, energy resources, and national security in that order.

Since that time, however, the science and energy communities have done little to embrace the Project. DOE now justifies the project almost solely for its contribution to Stockpile Stewardship. When Secretary Richardson certified a new cost and schedule baseline for the NIF to the Congress last fall, the only mission he discussed was Stockpile Stewardship, stating:

> The National Ignition Facility supports the Stockpile Stewardship Program, and is a vital element of it in three important ways: 1) the experimental study of issues of aging or refurbishment; 2) weapons science and code development; and 3) attracting and training the exceptional scientific and technical talent required to sustain the program over the long term.[2]

The notion that NIF is essential for Stockpile Stewardship is questionable. The NIF may not meet its technical goals, and even if it does, NIF's contribution to Stockpile Stewardship would be marginal.[3,4] Furthermore, Stockpile Stewardship is not the best way to manage the nuclear arsenal. Under Stockpile Stewardship, DOE plans to rely upon the NIF and a host of companion facilities to increase its understanding of nuclear weapons physics. DOE plans to use this improved understanding to develop complex computer codes in an attempt to correctly predict the detailed behavior of exploding nuclear weapons. This capability, if it is achieved, could be used not only to maintain the safety and reliability of the existing nuclear stockpile, but also to design new, more frightening nuclear weapons. Under Stockpile Stewardship, DOE plans to upgrade the performance of every weapon system in the existing stockpile and even has plans to develop completely new nuclear weapons.[5]

A recent report, by the author of this paper,[6] identifies three alternatives to Stockpile Stewardship, each of which offer improvements in maintaining the safety and reliability of U.S. nuclear weapons until they can be eliminated. Those alternatives would refocus DOE's efforts into preserving existing nuclear weapons as they are, rather than making improvements. DOE would do this by replacing nuclear weapons components that degrade with new ones as close to the initial designs as possible. The three alternatives are more in harmony with existing U.S. commitments in arms control than is Stockpile Stewardship and would better support additional efforts to reduce the danger from nuclear weapons. In addition, they are less costly than Stockpile Stewardship. None of the alternatives would need the NIF.

This report does not review the need for the NIF or the logic of Stockpile Stewardship. Previous reports by Tri-Valley CAREs and others, including "Nuclear Con-Fusion"[7] and "Managing the U.S. Nuclear Weapons Stockpile"[8] discuss those issues. The purposes of this report are to illuminate the full cost of building and operating the NIF and to draw attention to the likelihood that the NIF will not meet all of its performance goals.

Overview of Cost Increases and Schedule Delays

Early scoping studies for a precursor to the NIF had cost estimates as low as $677 million. Some major parts of the project were excluded from that estimate, however. When the NIF Project was formally approved in 1995, it had an estimated price tag of $1.1 billion and a completion date of 2002. In July 1997, DOE added $125 million to the cost estimate and delayed Project completion to 2003. This increase was due to a combination of increasing the scope of the Project and recosting some items. Then, after encountering significant technical problems in 1999, DOE completely "rebaselined" the NIF Project. In August 2000, Secretary Richardson approved a new schedule to complete the Project in 2008 at a total cost of $3.4 billion. This new estimate includes $1.2 billion in project-related activities that DOE chose to exclude from earlier cost estimates.[9]

If interest from the start of construction were included, the fully-loaded cost of the Project would balloon to $7.1 billion, if completed in 2008. Each year of delay would add $725 million.

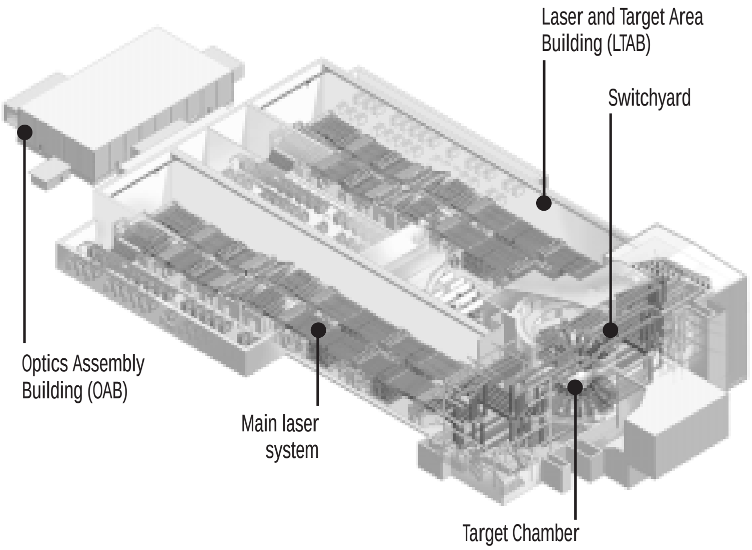
This report will show that DOE has still not included all relevant costs in the NIF Project and has underestimated others. In addition, it will describe significant technical hurdles, which could delay the Project another year or more, further increasing the cost. We estimate the full direct cost to complete the Project in 2008 would be $5.0 billion. If interest from the start of construction were included, the fully-loaded cost of the Project would balloon to $7.1 billion. Each year of delay beyond the 2008 target date would add another $325 in direct costs and $400 million in interest to the Project. If NIF were delayed by one more year (which we believe is a conservative estimate) the fully-loaded cost, with imputed interest, would be $7.8 billion. That is more than six times what DOE claimed it would take to build NIF when the project was first approved.

Even with the price of the Project soaring, it is questionable whether DOE will be able to meet its goals for the NIF. DOE has not been able to sufficiently control damage to optical components of the laser when it is operated at its highest energy levels. This problem, which was not fully appreciated when the Project began, could limit the energy from the lasers and the number of planned shots per year. Several other problems could also delay the Project further or prevent the NIF from operating as planned. In addition, the Department of Energy has not shown that it can fabricate fusion targets that meet the requirements for ignition. Thus, even if the NIF achieves full laser power, DOE may not meet its primary goal.

Project Description

The NIF is intended to create extremely high temperatures and pressures in pea-sized fuel pellets by focusing the light from the world's largest laser onto them. If DOE is successful, some of the pellets will explode like mini-hydrogen bombs. Figure 1 is a schematic diagram of the facility. To get an idea of its huge scale, the reader should note that the photo on the cover of this report is the inside of the target chamber. The target chamber appears to be a small ball in Figure 1.

Figure 1 — Schematic Representation of the NIF



The NIF design includes a 192-beam neodymium-doped glass laser, with each beam capable of discharging 20 kilojoules (kJ) of light energy in less than five-billionths of a second. That is the same amount of light emitted from a standard 60-watt light bulb in about fifteen hours. The lasers are to produce light in the infrared region of the spectrum, with a wavelength of 1.06 x 10^{-6} meters (i.e. 1.06 μm). Light of shorter wavelength (higher frequency) is more effective at transferring energy to the types of targets planned for use in the NIF. Therefore, a key element of the design is inclusion of a "frequency tripler" that will convert the infrared light at 1ω into its third-harmonic, 3ω, with a wavelength in the ultraviolet at 0.35 μm. This frequency conversion is accomplished by passing the light through crystals of potassium dihydrogen phosphate (KDP) and deuterated potassium dihydrogen phosphate (DKDP) in the final optics unit prior to the light being focused onto the target. The ability of the KDP and DKDP crystals and other components of the final optics to withstand the intense laser light, without being damaged, is critical to determining the success of the NIF.

From the final optics, the light enters the 33-foot diameter target chamber. The design requires the 192-beam laser to deliver 1.8 million Joules (MegaJoules or MJ) to targets. The target chamber must contain the energy from exploding fusion targets. It has four-inch thick walls and strong silica glass windows through which the light is focused. It also provides ports for scientists to insert sophisticated diagnostic equipment to collect data on experiments.

The 192 individual laser beams are combined into units of four as they enter the target chamber through 48 ports. This is the minimum number of beams required to provide the complete symmetry for imploding targets. The final optics assembly is attached to those ports at the entrance to the chamber. The target chamber and final optics must be sealed off from the atmosphere and placed under vacuum before the laser is fired at a target.

The NIF design requires over 3,000 large slabs of precision fabricated laser glass, weighing over 150 tons. It also requires 4,000 large lenses, mirrors, windows, and focusing devices (largely made from fused silica glass), and nearly 600 KDP and DKDP crystals. Almost half the cost of the NIF Project is for the design, procurement, and preparation of these and other optical components.

The NIF design is modular. The major components of the laser are designed to be assembled into "Line-Replaceable Units" (LRUs) and then inserted into a supporting infrastructure. There are 42 different types of LRUs. A total of 6,000 LRUs are scheduled to be installed in the NIF. During operation, DOE plans to remove and repair or replace malfunctioning LRUs from individual beam lines, without causing a significant impact on overall operations.

NIF Targets

A variety of different target designs might be used in the NIF for various weapons physics experiments. The most common target for ignition experiments, however, will consist of a small, hollow gold or gold-plated cylinder (typically one inch long and one-half an inch in diameter) called a "hohlraum". The hohlraum might typically contain a pea-sized pellet containing deuterium and tritium. (Deuterium and tritium are isotopes of hydrogen and are the predominant energy source in hydrogen bombs.) The walls of the pellet might be either plastic or beryllium metal. The laser light is to enter from the ends of the hohlraum and shine on its walls in circular rings. This is designed to heat the hohlraum to tremendous temperatures and cause it to emit intense x-rays. The x-rays in turn would bathe the fuel pellet, heating and compressing it. The outer layers of the fuel pellet would be blown off (ablated) from its surface. The reaction to this outward motion would further compress and heat the rest of the pellet, including the fuel.

If NIF works, the deuterium and tritium could be compressed to 20 times the density of lead and reach temperatures of 100 million degrees Celsius. At that point, nuclei of deuterium and tritium might begin to fuse together and, after emitting a high-energy neutron, form a helium nucleus (also called an alpha particle). The Alpha particles and the neutrons would move apart at high speeds and carry off tremendous amounts of energy. If enough fusion occurs, the pellet might explode with up to 25 times the 1.8 MJ of energy initially focused on the target from the lasers. The fusion of deuterium and tritium and other processes, which might take place in the hohlraums and the pellets that would be irradiated at the NIF, are akin to processes that occur in exploding nuclear weapons. The scale is enormously reduced, however. The yield of the maximum credible explosion from the NIF, which is 45 MJ, is equivalent to an explosion of about 20 pounds of TNT.

Status of the Project

Much of the conventional construction (e.g. the building that will house the laser) for the NIF is complete. The majority of the remaining work consists of fabricating, installing, aligning, and testing the delicate optics that form the guts of the laser. The next largest pending activity is completion of the design, fabrication, and installation of the sensors, computers, and control systems that will be necessary to operate the NIF. Those complex and delicate operations are scheduled to take the remaining seven years until project completion in 2008. First light from eight of the 192 beams (eight beams are called a bundle) is scheduled to occur in June 2004. Initial experiments using those beams are scheduled for December 2004.

Figure 2 is a recent aerial photo of the NIF construction site. The parked cars in the lower right corner of the photo provide a sense of scale. The huge Laser and Target Area Building (LTAB) that will house the lasers, capacitors, and target chamber is more than 90 percent complete. Large capacitors are needed to store energy and at the proper time deliver it to flashlamps that convert the electrical energy to light. The light shines on the neodymium-glass slabs, where the laser beams are created.

Figure 2 — Aerial photo of the NIF construction site, early 2001.

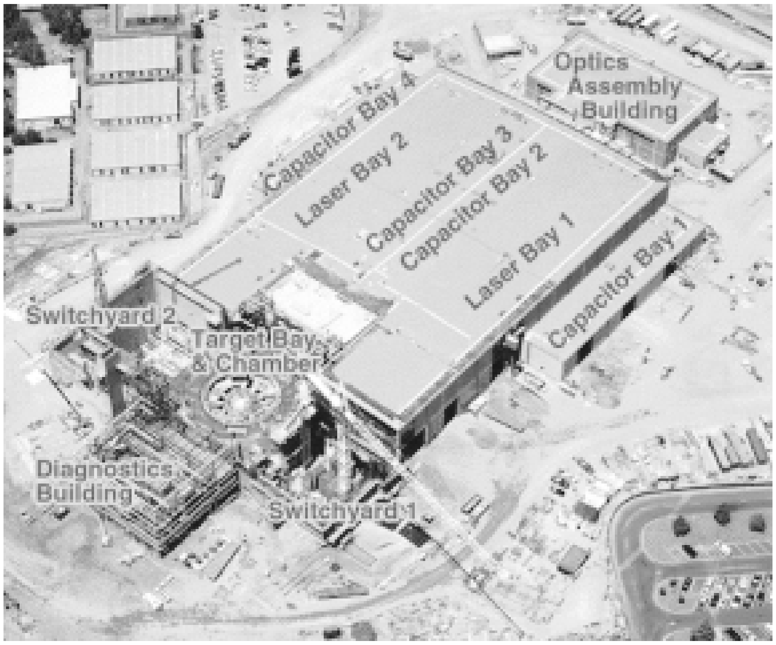


Figure 3 is a photo of the inside of one of the two laser bays. This large room will eventually house 96 of the 192 lasers. The equipment shown is largely supporting structures. Installation of the steel frames that will house the LRUs and enclose the laser beams is ready to begin.

Figure 4 shows the 33-foot diameter target chamber in place, with covers over the penetrations for the final optics units, diagnostic instrumentation, target handling equipment, vacuum systems, and other target area systems. The large square penetrations, several of which can be seen in the photo, are designed to accommodate the 48 final optics units, through which the laser light is to be focused onto targets.

Installation of the final optics assemblies, diagnostic equipment, control and vacuum systems, and target handling equipment is pending.

The steel structure of the "switchyard" for half of the beams has now been installed. The switchyard is designed to hold the many mirrors needed to turn and direct the beams to the 48 separate entrances into the target chamber through the final optics. The Optics Assembly building (OAB) has been completed and certified for clean room operations. Most of the optical components are to be delivered to the OAB from offsite contractors. There, Project staff are to inspect and in many cases polish and apply coatings to the components and insert them into the LRUs. Other LRUs are scheduled to come fully assembled and will only be inspected and tested in the OAB and held for transport to the LTAB for insertion into the laser system at the proper time. A variety of specialized assembly, handling, and transport equipment is now being installed in the OAB in order to support LRU assembly. The job of inserting the LRUs into the laser system in the LTAB will be difficult, because the building is very crowded and is not a clean environment. A major reason why DOE increased its cost estimate for the NIF in August 2000 and delayed the construction schedule was that it had underestimated the difficulty of this task.

Figure 3 — Inside Laser Bay 2 at the NIF, December 2000.

Figure 4 — Upper half of the NIF Target Chamber, November 2000.

Few of the optical elements have been fabricated. DOE has selected contractors to produce the materials for the various types of optics, including the laser glass, the KDP and DKDP crystals, and the fused silica optical components. Those contractors are currently performing final test runs or in some cases beginning initial production runs. Some of the components from these runs will not meet the final specifications for the NIF. Failing to meet the specifications will result in significant cost increases as is discussed below.

As of the beginning of Fiscal Year 2001 (October 2000), $1.7 of the $3.4 billion that the Department of Energy estimates it will cost to build NIF had been appropriated by Congress and $1.2 billion had already been spent. To date, most of the spending has been on the easy part of the project — the conventional construction of the buildings. The project now faces the more challenging task of building and aligning the laser beams and associated equipment.

History of NIF Costs Increases and Schedule Delays

DOE has significantly increased its cost estimate and delayed the schedule for the NIF three times since the Secretary of Energy first approved proceeding with the Project. With seven years remaining before the full NIF is to be commissioned, there is every reason to expect more delays and cost increases.

Early Cost and Schedule Estimates

In January 1993, the Secretary of Energy approved the "Justification of Mission Need," which authorized work to begin on a Conceptual Design for a National Ignition Facility. In its FY 1994 Institution Plan[10], Lawrence Livermore National Laboratory estimated that a glass laser facility capable of delivering 1.8 MJ on target and igniting fusion capsules could be built for $677 million. That estimate, however, does not include the cost of new buildings to house the laser and support facilities and it was based on very preliminary design information. In addition, it was in 1995 dollars and did not escalate the total to reflect the reduced value of the dollars in the years in which they would be spent, as is customary.

The NIF Conceptual Design Report (CDR) was completed in May 1994. The CDR officially established the primary requirements for the Project, such as the number of beams, energy per beam, wavelength, number of shots per year, etc. It also established a large number of detailed requirements that the design would have to meet. At the completion of the CDR, DOE produced the first cost estimate for the Project based upon detailed analysis of the proposed design. That estimate gave a Total Project Cost (TPC) of $1.073 billion. The CDR Report also projected that construction would be complete in July 2002 and that operations would begin in October 2002. Based on the findings of the CDR, DOE requested and Congress approved initiation of a formal construction project with the 1996 Budget.

The Title 1 Cost Estimate

In January 1996, the NIF Project Team, led by Lawrence Livermore National Laboratory, began work on a more detailed design for the NIF, referred to as Title 1 Design. During Title 1 Design, the Project Team produced preliminary engineering drawings for the buildings and major components of the Project. The Team also reevaluated the detailed Project requirements based on requests from potential users. At the conclusion of the Title 1 Design, in March 1997, DOE approved several new requirements proposed by the Project Team, including:

- Extra cooling for the flashlamps that power the laser to allow for increasing the shot rate above 600 per year;

- New optical components (beam smoothing) designed to make the laser beams more uniform;
- Structural modifications to the switchyard and target area that would allow future changes to provide for "direct-drive." Direct-drive is an alternative means of imploding fusion capsules in which the laser beams are focused directly upon the capsule instead of on a hohlraum that contains the capsule;
- Features requested by the Defense Special Weapons Agency of the DOD, which could improve the use the NIF to test the resistance of military hardware to the effects of nuclear weapons; and
- The ability to reduce the spot size at the focus of the laser beams for weapons physics experiments.

In addition, during Title 1, DOE increased the cost estimates for several other items and added the cost of the Optics Assembly Building, which had previously been viewed as an infrastructure requirement funded outside of the Project. DOE also delayed the completion of construction by one year from July 2002 to July 2003.

In an attempt to mask the increasing cost of the NIF, DOE removed several items, which would not be needed during the first few years of operation, from the scope of the Project. Those items, such as extra radiation shielding in the target area, would be needed after the introduction of tritium and would eventually have to be funded. DOE removed them from the Project, however, to limit the apparent increase in its cost and reduce potential criticism from Congress that the one-year old project was already experiencing substantial cost overruns.

For the same reason, DOE also shifted the cost of initial testing of some of the lasers from the Project budget to the operating budget, where it would be less visible. That is because Congress appropriates specific dollar amounts to each construction project every year, but it combines funding for numerous operating programs into large budget accounts, where they have less visibility. Under the previous schedule, the Project budget was responsible for initial testing and certification of all 192 laser beams. Experiments were scheduled to begin with the full complement of 192 beams having been certified and available in October 2002. Under the new schedule, initial experiments could begin with eight beams as early as September 2001. However, as additional beams were completed, some of the cost of testing and certifying them would be borne by the operating budget rather than the Project account. Furthermore, the full complement of 192 beams would not be tested, certified and available for experiments until October 2004 — a delay of two years, rather than the one-year delay the DOE officially claimed for the completion date of the Project.

Even with this shifting of costs from the Project to the operating budget and to future capital projects, DOE's official estimate of the Total Project Cost (TPC) for the NIF increased by $126 million to $1.198 billion.

Outside Critics Foresaw Technical Problems, Cost Increases, and Schedule Delays

Critics of the NIF have long predicted that the Project would have technical problems and would cost more, and take longer to build, than DOE claimed. As early as 1995, the “Green Scissors Report” noted $1.8 billion could be saved by terminating the NIF and that its price tag was sure to rise.[11] Later that year, an economic analysis of NIF construction concluded, “NIF may overspend early in the project cycle and may experience significant delays due to the attempt to ‘push’ the project in the first four years.”[12] A 1998 Report on the NIF for Tri-Valley CAREs titled, “Nuclear Con-Fusion — The National Ignition Facility: Flawed Rationale, High Cost, and Security Risks” placed the cost of the NIF at $5 billion and climbing (including operating costs) and concluded that the technical goals of the Project exceed DOE’s grasp.[13]

From the time of the conceptual design to the present, scientists within and outside of DOE’s Inertial Confinement Fusion program have continually questioned whether ignition could be achieved in the NIF. DOE’s history of ignoring such concerns is detailed in a June 2000 report from the Natural Resources Defense Council titled, “When Peer Review Fails.”[14]

The August 2000 “Rebaseline”

DOE Acknowledges Cost and Schedule Problems

Critics of the NIF were vindicated, in August of 1999, when officials from DOE and LLNL first publicly acknowledged that technical problems would delay completion of the NIF and would increase its construction cost. DOE initially estimated the delay would be 18 months and the cost would increase by $300 million. As is typical of DOE, those would prove to be significant underestimates.

Senior Livermore officials connected with the Project had been aware that there were problems more than a year earlier.[15] However, they withheld that information from the Director of the Laboratory and from DOE. As late as June 11, 1999, Secretary Richardson, reflecting the information available to him at the time, had publicly announced that NIF was on schedule and on budget. In addition to the technical problems that were responsible for the overruns, the fact that the Project was able to cover up such a large problem revealed substantial management shortcomings at DOE and LLNL. A report released by the U.S. General Accounting Office in August 2000 (referred to below as the GAO NIF Report) provides additional details regarding the management problems and the cover-up.[16]

The main technical reasons DOE gave for the delays and cost overruns were:

- They had underestimated how difficult it would be to assemble and install the intricate and tightly packed laser system and meet the stringent cleanliness standards for the laser, while working in the relatively dirty environment of the Laser and Target Area Building (LTAB); and
- They had underestimated the cost of fabricating some of the LRUs, which contain major components of the laser system.[17]

The Rebaselining Process

Once these problems were revealed, the Department of Energy directed the NIF Project Team to develop a new baseline cost and schedule plan. After an initial attempt at modifying the previous plan, the Project Team eventually developed a new bottoms-up baseline. The new plan involved a rethinking of the strategy for constructing the NIF, installing the laser components, and commissioning the individual laser beams. Under the new strategy, the time allotted to installing the infrastructure to support the laser system was stretched out considerably. The first bundle of laser beams would not be turned on until the infrastructure for all of the beams had been completed – three years later than under the previous schedule. Installation of the LRUs to complete the laser system was also slowed. According to DOE, however, the new order in which the laser beams were scheduled for commissioning would reduce the impact of the overall delay in the Project. With the revised strategy, the Project Team reexamined thousands of individual work packages and developed a new bottoms-up cost and schedule plan.

In an attempt to firm up support for the Project from Congress, which was growing skeptical of DOE's credibility, DOE established two separate committees to review the new baseline plan. One was a subcommittee of the Secretary of Energy Advisory Board (SEAB), called the National Ignition Facility Laser System Task Force[18] (referred to below as the SEAB NIF Task Force). The other was an ad hoc committee, consisting primarily of employees of DOE and its contractors, called the Rebaseline Validation Review Committee[19] (referred to below as the "Carlson-Lehman" Review for its Chair, Kathleen Carlson, Manager of DOE's Nevada Operation Office and its Deputy Chair, Daniel Lehman, Director of Construction Management for DOE's Office of Science). DOE touted both of these as independent review committees, even though they were comprised primarily of DOE employees and contractors. After gaining the approval of both committees, DOE officially adopted the new baseline and provided the final certification for the revised cost and schedule to the Congress on September 14, 2000.

DOE's process for review and approval of the new baseline has met with considerable controversy. On October 11, 2000, the Natural Resources Defense Council (NRDC) and Tri-Valley CAREs filed suit in the Federal District Court for the District of Columbia alleging that DOE violated the Federal Advisory Committee Act (FACA) in the course of soliciting outside advice from both of these pseudo-independent committees. With regard to the Carlson-Lehman Review (Rebaseline Validation Review), the suit charges:

> DOE has not complied with FACA in any fashion with respect to the Rebaseline Validation Review – the meetings were not open to the public, the existence of the Committee was not made public, the required Committee materials were not made publicly available, and DOE never filed a charter for the Committee. . . . DOE also never made the required findings that the Rebaseline Committee was "in the public interest," was "fairly balanced," and was free of members with inappropriate special interests. . . .[20]

The FACA suit also charges that eleven of the so-called "independent" members of the Carlson-Lehman Committee had serious financial or career conflicts of interest, and "seven of them had individual consulting contracts with Livermore in areas directly related to the NIF project," according to affidavits filed in the case.

On March 28, 2001, Federal District Judge Emmet G. Sullivan ruled in favor of the plaintiffs motion for a preliminary injunction to prevent DOE from using the reports until the case gets decided on its merits in late spring or early summer. DOE had initiated a follow-up committee, with the same membership as the Rebaseline Validation Review, to provide an updated "NIF Status Review." The court, however, issued an order preliminarily enjoining DOE from further funding, supporting, or permitting work on developing the recommendations of the NIF Status Review Committee. Judge Sullivan found that the plaintiffs "have demonstrated the requisite likelihood of success on their claims that FACA applies" to both the August 2000 NIF Rebaseline Validation Review and the NIF Status Review Committee.

The Judge's ruling casts doubt on the "independence" of the two Committees and on their validation of DOE's August 2000 schedule and cost estimate for the NIF.

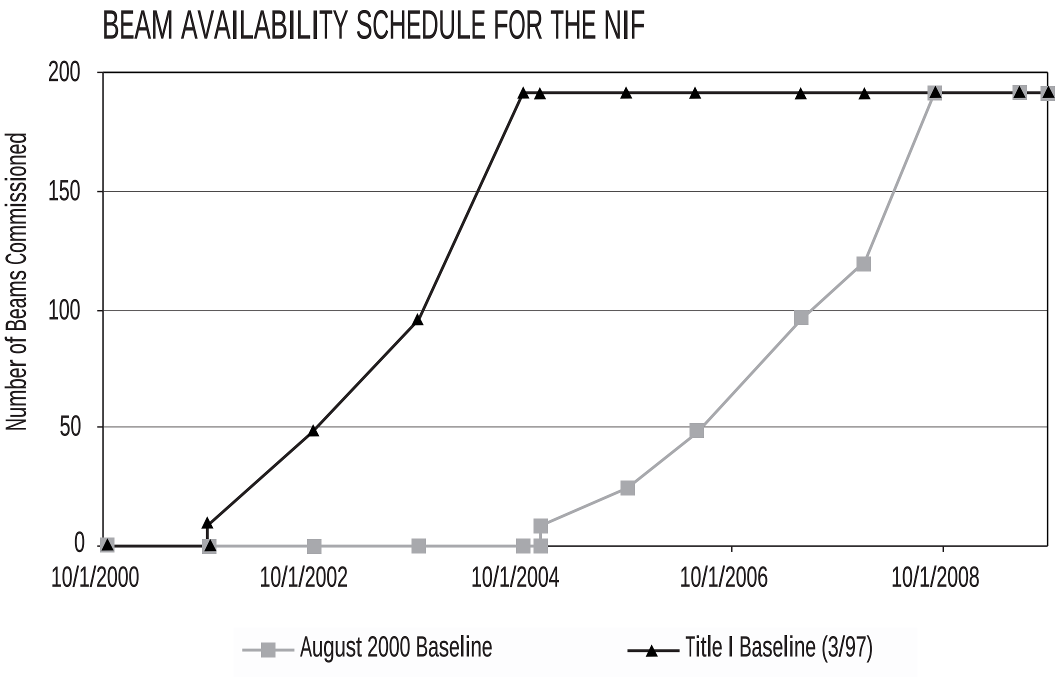
The New Schedule under the August 2000 Baseline

The August 2000 rebaseline introduced a significant delay in the Project schedule. The schedule now calls for "first light," i.e. when the first eight beams will be turned on, in June 2004. Those first eight beams must then be aligned and tested before being commissioned and turned over to the operating staff to begin experiments, which is scheduled for December 2004. That date is more than three years later than the scheduled September 2001 startup of experiments with eight beams under the Title 1 plan from March 1997. The additional time is needed primarily to install the beampath infrastructure and LRU's to the required standards of cleanliness. Under both the old and new schedules, additional beamlines are to be made available for experiments as soon as they are installed, tested, and commissioned. The new schedule calls for Project completion, when all 192 beams will be available for experiments, in September 2008. That is four years later than the date that all the beams were to be available for experiments under the Title 1 schedule and six years after the original 2002 completion date. The numbers of beams available under the 1997 schedule and the August 2000 baseline are compared in Figure 5.

> The Judge's ruling casts doubt on the "independence" of the two Committees and on their validation of DOE's August 2000 schedule and cost estimate for the NIF.

The Department of Energy claims that the effect of the delay on weapons

Figure 5



physics experiments and preliminary experiments leading to ignition will not be as great at it may appear simply by comparing the numbers of beams available. That is because the new schedule adds beamlines in a manner designed to provide greater symmetry for hohlraum shots when the levels of 48 and 96 beams are achieved than under the previous plan. This may have some validity, but under the new schedule, the date when 48 beams are scheduled to be commissioned is still a full 20 months later than when the full system would have been in operation under the previous schedule. Similarly, 96 beams will not be commissioned until 32 months after the full system was to have been in operation. Furthermore, because of technical problems that were revealed with the new baseline (which are discussed extensively below), individual beamlines will be restricted to operate at no more than one-half of the full design energy until at least 2007. Thus, operation of the NIF in a manner remotely approaching its initial promise has been significantly delayed.

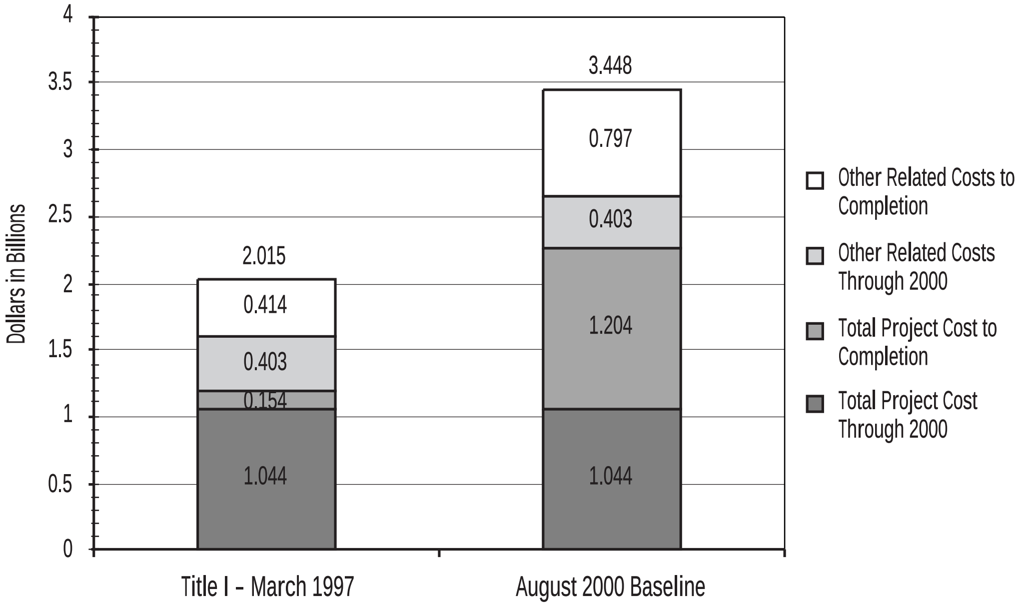
The August 2000 Baseline Cost Estimate

DOE's estimate of the Total Project Cost (TPC) for NIF under the new baseline is $2.248 billion, which is an increase of $1.050 billion, or nearly 90 percent, over the previous estimate of $1.198 billion. Since the new baseline is a bottoms-up estimate and uses different categories of costs than the previous estimate, it is impossible to tell exactly where the increases have occurred. According to DOE, however, the largest cost increases are in the area of beampath infrastructure construction and laser special equipment[21] (i.e., construction of the supporting structure and utility systems for the laser and acquisition, inspection, testing, and installation of the LRUs). There are also smaller increases to the cost estimates for procurement of the optical components and for control systems and target systems. In addition, the amount reserved for contingencies is increased from 15 percent to 26.7 percent of the estimated remaining cost of the Project. The total amount of contingency funding in the new TPC is $252 million, compared to the previous value of $132 million.

DOE has also acknowledged for the first time that there are substantial "Other Related Costs" of building NIF that are funded out of DOE's general operating budget, rather than appropriated specifically to the NIF Project. Until now, this funding, which includes items such as R & D in support of the Project, has not been controlled by the Project and was not included in the estimated Total Project Cost (TPC). DOE estimates these Other Related Costs will total $1.2 billion through Project completion in 2008, which brings its estimate of total project-related costs to $3.448 billion. While it was not included in its previous cost estimates, DOE now estimates that Other Related Costs under the previous baseline would have been $817 million, bringing DOE's revised cost estimate for the Title 1 baseline to $2.015 billion. Figure 6 compares the Total Project-Related Cost for the August 2000 Baseline with that of the revised Title 1 Cost Estimate. As you examine Figure 6, keep in mind that DOE's cost estimates do not tell the whole story. The tops of the bars will rise considerably as you progress through this report. We will uncover additional costs, not reflected in Figure 6, and highlight problems that are likely to cause more schedule delays and cost increases.

Figure 6

COMPARISON OF OLD AND NEW DOE BASELINES



DOE's Cost Estimate Does Not Include All Project-Related Costs

We have identified two types of project-related costs that are not included in DOE's current baseline cost estimate. They are project-related costs charged to operating programs and costs for anticipated Project enhancements. These are described below.

DOE's Cost Estimate Excludes $1.332 Billion in Project-Related Costs Charged to Operating Programs[22]

DOE's August 2000 baseline cost estimate for the NIF does better than previous cost estimates in including some project-related costs that are funded from operating programs accounts. It, however, still excludes several categories of such costs, which are described below and summarized in Table 1.

DOE Cost Categories for Construction Projects

There are numerous ways to define the cost of large projects such as the NIF. The most restrictive definition is to count only the cost of the actual design and construction of the facility. That is the cost of preparing engineering drawings for the Project and the cost of building, acquiring, and installing facilities and equipment. The Department of Energy calls this the "line-item" cost or the Total Estimated Cost (TEC). Once a construction project is initiated, DOE requests a specific amount from the Congress for these brick and mortar-type activities as a distinct element (or line-item) in its Budget request. This number is unambiguous and is easy to track through the budget process and from year-to-year. DOE's current estimate of the total line-item (TEC) cost for the NIF Project is $2.095 billion out of its estimate for all project-related costs of $3.448 billion.

The next class of construction costs involves activities that are paid out of operating budget accounts, but without which the facility could not be completed and brought into operation. This includes activities such as R & D necessary to complete construction, training and staffing, start-up planning, and costs for operational readiness reviews. In the DOE terminology, they are referred to as "Other Project Costs (OPC)." When the OPC is added to the line-item costs (TEC) the result is the "Total Project Cost" or TPC. DOE specifies the total spending on OPC for each year of the Project in its Construction Project Data Sheet. However, details of the OPC costs are not easily identified in DOE Budget documents, because they are usually lumped together with other programmatic activities. From the beginning of the NIF Project, DOE used a very restrictive definition of what to include in the OPC. For example, R & D intended to improve the operation of the NIF was not counted, even if such R & D had to be performed and had to be successful for the NIF to meet its design requirements.

From the beginning of the NIF Project, DOE used a very restrictive definition of what to include in its cost estimate.

At the conclusion of the Title 1 Design, DOE revised the Project schedule to begin operation with some beams while construction continued on the rest of the facility. As was discussed above, DOE then removed much of the cost of initial beam operations from the OPC estimate in order to limit the increase in the TPC. DOE simply stopped counting this activity in its cost estimate. In March 1977, DOE reduced its already low estimate of OPC from $231 million to $153 million. DOE did not modify that latter figure when it rebaselined the Project in August 2000. Thus, the current estimate of the TPC is the estimated line-item cost (TEC) of $2.095 billion plus the estimated OPC of $153 million for a TPC of $2.248 billion.

When it transmitted the new baseline to Congress in August 2000, DOE finally acknowledged that significant project-related costs were not included in the TPC. DOE created a new category of project-related costs that it called, “Other Related Operation and Maintenance Costs (OROMC).” DOE estimated those costs to be $1.2 billion, which, when added to the TPC brought its estimate of total project-related costs to $3.448 billion. DOE has supplied very little information regarding what is included in this estimate of OROMC beyond a year-by-year breakout of the $1.2 billion total. DOE’s only description of this category of funds appears in a footnote to the Construction Project Data Sheet, which identifies the source of those funds as “Funding previously requested and appropriated in the Inertial Confinement Fusion Program and, beginning in FY 2001 under Readiness in Technical Base and Facilities, NIF Operations.”

What Does DOE include under OROMC in the August 2000 Baseline?

The August 2000 baseline includes $61 million for Other Related Operation and Maintenance Costs (OROMC) in 2001.[23] That figure cannot be found in the DOE 2001 Budget request for Readiness in Technical Base and Facilities (RTBF) or anywhere else in DOE’s 2001 request. One must apply the skills of a detective to surmise what is included in the DOE estimates. DOE’s 2001 Budget does request $53.4 million in RTBF for the following category:

> **National Ignition Facility (NIF) Operations at Lawrence Livermore National Laboratory (LLNL),** includes continuing the ramp-up of operations activities in the Optics Assembly Building and other support facilities at the NIF, training of NIF operators, and inventory maintenance to support operating activities.[24]

The above description is close to the one sentence definition of OROMC that appears in the Construction Project Data Sheet. The major difference is that it includes only activities at LLNL. While LLNL is the lead laboratory, other DOE laboratories are performing R & D and other activities in support of the NIF. The DOE Budget documents don’t show the costs of NIF-related activities at the other laboratories, as they are included in broad budget categories for those labs. It is possible that the difference between the $53.4 million figure above and DOE’s 2001 estimate of $61 million for OROMC is accounted for by spending from other laboratories. We assume that is true and that the above category of spending (with spending at other labs included) accounts for the entire $1.2 billion that DOE counts in its cost estimate under OROMC.

The next five sections of this report each discuss a category of cost that DOE has chosen not to include in its cost estimate and presents our estimate of projected spending for that category.

DOE's Estimate Excludes $400 Million in Costs for NIF Program Facilities and Infrastructure Buildup Activities

There is another category of spending on NIF in DOE's 2001 Budget request for RTBF, which it describes in the following convoluted manner:

> **NIF Program Facilities and Infrastructure Buildup Activities at LLNL,** include performance support and risk mitigation R & D for laser components, optics and laser systems; and conversion of support facilities from Nova capabilities to NIF requirements.[25]

DOE's 2001 Budget request for that category is $47.4 million. Everything in the above description for NIF Program Facilities and Infrastructure seems directly related to the NIF Project, but apparently, none of it is included in DOE's estimate of OROMC in the August 2000 baseline. According to DOE's 2001 Budget request, DOE spent $48.9 million on these activities in 2000 and $55.9 million in 1999. Assuming that annual spending on these activities would gradually decrease to $30 million in 2004 and $10 million in 2007, we estimate that **including the cost of NIF Program Facilities and Infrastructure would add a total of $400 million to DOE's August 2000 Baseline cost estimate through 2008.**

DOE's Estimate Excludes $627 million in Costs Identified by GAO

In addition to NIF-related costs in the RTBF portion of DOE's 2001 Budget, there are several categories of NIF-Related activities described under what DOE calls "Campaigns." Campaigns are primarily research and development activities in support of Stockpile Stewardship. One of the campaigns is named, "Inertial Confinement Fusion Ignition and High Yield." Much of the work in that campaign directly supports the NIF Project and it should be included in the cost estimate. For 2001, however, DOE included only $5.9 million of the $121 million requested for this campaign in the NIF OPC.[26] The rest is excluded from DOE's August 2000 cost estimate.

The GAO NIF Report has identified two categories, "**Target Design and Fabrication**" and "**NIF Support from Other Laboratories**," which it believes should be included in the cost estimate for the NIF Project.[27] According to GAO, the first category includes only activities at LLNL and the second category is primarily target design and fabrication activities at other laboratories. Since NIF would be a useless hulk without targets to shoot at, we agree with GAO's conclusion that these costs should be included in the cost of the NIF Project and have included them in our cost estimate.

Based on information supplied by DOE, GAO estimates that DOE will spend $34 million in 2001 and $491 million from 1996–2007 on Target Design and Fabrication and $11 million in 2001 and $136 million from 1996–2007 on NIF Support from Other Laboratories. Those two categories do not directly correspond to any of the budget categories in the Inertial Confinement Fusion

Ignition and High Yield Campaign. According to GAO, however, DOE officials told them that the funds for those activities are included in the ICF Campaign in the 2001 Budget.[28] The total for 2001 of $45 million for GAO's two categories is close to the $47 million that DOE requests in its Budget under the Inertial Confinement Fusion Ignition and High Yield Campaign to "Conduct experimental and calculational activities aimed at developing the physics basis for indirect-drive and direct-drive ignition." It is likely that the target design activities are included in that category. We include GAO's estimates for the costs of "target design and fabrication" and for "NIF support from other laboratories" in our cost estimate. This adds $491 million and $136 million respectively to DOE's August 2000 baseline cost estimate.

DOE's Estimate Excludes all Costs for Diagnostics and Instrumentation for Target Experiments

DOE's August 2000 Baseline cost estimate includes about $51 million for laser system diagnostics. That is the instrumentation and test equipment designed to assess the status and performance of the laser system and provide information needed for controlling the laser beams. The baseline also includes several million dollars for diagnostic equipment to collect and analyze data emitted from special targets that it plans to use to assess the performance of the laser. DOE refers to those diagnostics as the "core set." The DOE cost estimate does not include any funds for the highly technical diagnostic equipment and instrumentation that will be needed to collect and analyze data from target experiments in the NIF. Since NIF is useless without diagnostics, their cost should be included in the estimated total project-related costs.

The DOE cost estimate does not include any funds for the highly technical diagnostic equipment and instrumentation that will be needed to collect and analyze data from target experiments in the NIF.

DOE is funding all the costs of developing, designing, building, and installing target diagnostics and instrumentation for the NIF from its operating programs budgets. The Department has not made any information about the total cost of NIF diagnostics public. In preparation for a conference on NIF diagnostics that was held in June 2000,[29] a LLNL web site listed 30 types of diagnostic equipment beyond the core set that were requested by users for "phase one" and an additional 53 types of equipment for phase two diagnostics. The equipment lists included: high energy x-ray imagers, neutron imagers, several spectrometers at wavelengths from the visible to the x-ray, charged particle detectors, fast framing cameras, and numerous other types of highly specialized detectors. This planned suite of target diagnostics will certainly be much more extensive and costly than the laser characterization and core set diagnostics.

One of the subcategories of funding in the Inertial Confinement Fusion Ignition and High Yield Campaign in DOE's 2001 Budget request is to; "Develop the initial set of NIF core diagnostics and laser characterization diagnostics, and develop advanced target diagnostics." The inclusion of core diagnostics and laser characterization diagnostics in that subcategory of operating funds raises questions, since NIF Project documentation indicates those diagnostics are funded within the line-item for the Project. Regardless of the answer to that question, these operating funds are definitely not included in the August 2000 Baseline cost estimate. Thus, the funds requested in that category represent the minimum amount that DOE may be spending for NIF diagnostics out of operating funds. Additional spending on diagnostics may be hidden in other budget categories. DOE requested $16.9 million for that activity for 2001 and the 2001 Budget indicated that $8.3 million was spent in 1999 and $12.9 million in 2000. Based on those figures, and in comparison to the $51 million included in the Project for laser diagnostics, we estimate that the total cost of target diagnostics adds $175 million to DOE's August 2000 cost estimate.

DOE's Estimate Excludes the Cost of the Cryogenic Target Positioning System

DOE has not yet developed a system for getting tiny "cryogenic" targets into the large target chamber and holding them in place. Furthermore, it has not included the cost of developing and building a Cryogenic Target Positioning System in its cost estimate for the NIF. Cryogenic targets must be maintained at extremely cold temperatures, so the fusion fuel (deuterium and tritium) will be in a solid state. Positioning these targets is a challenging task. The cryogenic positioner must insert, align and hold the delicate targets steady to within 50 µm (about 0.002 inches) inside the 33-foot diameter chamber. It must do this without blocking the paths from any of the 192 laser beams or the view to the numerous types of diagnostic equipment, all the while maintaining the targets at a temperature of less than 20 degrees Celsius above absolute zero.

One of the primary requirements of the NIF design is that it "shall be capable of target operations with both cryogenic and non-cryogenic targets containing fusion fuel."[30] All the target designs, which are predicted to ignite at the energies available in the NIF, are cryogenic targets. Despite the fact that the Cryogenic Target Positioning System is required for ignition, DOE has not included its cost in the NIF Project. Rather, funding to "Define, prototype, design, fabricate, test and deploy the NIF Cryogenic System" is included in DOE's 2001 Budget within the Inertial Confinement Fusion Ignition and High Yield Campaign. The 2001 Budget requests $10 million for the first year of funding for this project. DOE has not released any information regarding its total cost. We estimate that the Cryogenic Target Positioning System will add $100 million to DOE's August 2000 baseline cost estimate. If the Project were delayed because DOE has difficulty meeting the challenging design requirements for the Cryogenic Target Positioning System, its cost would increase considerably more.

We estimate that the total cost of target diagnostics adds $175 million to DOE's August 2000 cost estimate.

DOE's Cost Estimate Excludes $30 Million for Items Shifted to the Operating Budget in 1997

When DOE revised its cost estimate for the NIF at the end of Title 1 Design, it shifted the cost of several items, which would not be needed for two or three years after operations began, from the line-item Project to the operating budget. DOE

Table 1

NIF PROJECT-RELATED SPENDING FROM OPERATING ACCOUNTS THAT IS NOT INCLUDED IN DOE'S AUGUST 2000 COST ESTIMATE

(Dollars in Millions)

CATEGORY	ESTIMATE OF ADDITIONAL COSTS
NIF PROGRAM FACILITIES AND INFRASTRUCTURE	$400
COSTS IDENTIFIED BY GAO	
Target Design and Fabrication	$491
NIF Support From Other Laboratories	$136
TARGET DIAGNOSTICS AND INSTRUMENTATION	$175
CRYOGENIC TARGET POSITIONING SYSTEM	$100
ITEMS SHIFTED TO THE OPERATING BUDGET IN 1997	$30
TOTAL	$1,332

did not include the cost for those items in its August 2000 baseline cost estimate. The items that were shifted out of the cost estimate include: target bay shield doors, which will be needed to provide adequate protection to workers from radiation if ignition experiments are conducted; decontamination equipment for the target chamber, which will be needed if high yield experiments are conducted; and additional maintenance equipment to replace LRU failures more frequently after the number of shots per year increases from the initial rate of 600 per year.

In 1997, these items were estimated to cost $10 million in 1997 dollars, without contingency. We adjusted that cost for the likelihood that higher than anticipated rates of LRU replacements will be necessary, because there will be more damage to the final optics from high fluences than was anticipated in 1997. We also made adjustments for contingency funds, escalation to 2007, and the overall increase in the cost of the Project. Thus, we added $30 million to the DOE August 2000 baseline cost estimate for these items.

Estimated Costs for Future Project Enhancements

DOE has had plans for several enhancements to the NIF Project at least since the completion of the Title 1 Design. At that time, changes were made to the design in order "not to preclude" the addition of some of these project enhancements. They include: the ability to do direct-drive experiments, the addition of a second target chamber, and operation at additional frequencies (1ω and 2ω). Other enhancements have been proposed by recent review committees including: an increase in the number of laser slabs (and other associated equipment) from sixteen per beam to eighteen per beam (11/5 design to 11/7 design) and enhanced use of other Inertial Confinement Fusion (ICF) facilities to lessen the impact of the delay in NIF. None of the costs for these enhancements is included in DOE's August 2000 baseline cost estimate. They are discussed in the following five sections and summarized in Table 2. We have assigned these future costs to two categories — those that would be incurred before the scheduled project completion in 2008 and those that would be incurred after 2008. Since we are estimating the cost to build the NIF in accord with DOE's schedule for operation in 2008, we include in our estimate only those costs that might be incurred before 2008. The cost of project enhancements that might be added after 2008 is included when we estimate the cost of operating the NIF later in this report.

Adding a Second Target Chamber Would Cost $400 Million

From the beginnings of the NIF Project, several potential user communities had their sights set on not just one, but possibly two or more additional target chambers. The weapons physics community staked its claim on a second target chamber during the conceptual design phase of the Project as follows: "The weapons program needs a second target chamber that is initially fed by 10 to 20% of the NIF beams. An additional design requirement will be the capability for upgrading this second chamber to provide it with all the capabilities of the first. This upgrade will permit sustaining a high shot-frequency rate by switching to the alternate chamber as the other cools."[31]

The Defense Nuclear Agency (DNA), which at the time was the DOD agency in charge of testing military equipment for the effects of nuclear weapons, proposed the following option in 1994: "A separate large test chamber for all 192 beams would be added to the first main chamber of the NIF, dedicated to DNA use [i.e. effects testing]. This option could allow a higher routine yield and a larger number of such shots, larger test articles, and a capability to handle small, non-critical amounts of fissionable material. This option is estimated to cost less than $150 million additional."[32]

We estimate that a second target chamber would cost $400 million if designed and built from 2011 through 2015.

Not to be outdone, the inertial fusion energy (IFE) community staked its claim thusly; "Many IFE experiments will involve various amounts of liquid and ablated solid test samples which will condense or solidify on the NIF chamber walls and optics windows. ... These debris problems [may] turn out to be incompatible with the main NIF target chamber, or result in long chamber recovery times for cleanup. These IFE experiments can benefit from the addition of a small test chamber of one to two meters diameter using laser-generated x-ray/debris targets with about 400 kJ laser energy."[33]

The "Facility Use Plan for the National Ignition Facility" released in 1997 continued the call for additional target chambers, stating: "The facility is designed to allow the addition of more target chambers. For example, an additional target chamber with full energy capability could be added by moving the turning mirrors in the switchyard and extending the beams beyond that target area by using additional spacial filter transport assemblies. In addition, target chambers accommodating less than full energy may be possible with less-expensive beam transport. Several suggestions have described the usefulness of a second target chamber."[34]

Calls for additional target chambers have been muted with the recent delays and cost overruns in the NIF Project. Nevertheless, the basic design requirements for NIF still state that, "The baseline facility design shall not preclude future addition of target chambers for additional weapons physics and/or radiation effects testing."[35] Should NIF be completed, the calls for additional target chambers would likely be renewed shortly thereafter. We estimate that a second target chamber would cost $400 million if designed and built from 2011 through 2015.

Adding Full Capability for Direct-Drive Experiments Would Cost $50 Million

During the Title 1 Design Review for the NIF, potential users requested that DOE add the capability to do direct-drive experiments. In direct-drive the laser beams would impinge directly on capsules containing fusion fuel instead of shining on hohlraums, which in turn bathe the capsules in x-rays. DOE's computer codes predict that igniting pellets using direct-drive will require greater symmetry and smoother beams than is planned for indirect-drive. DOE could accommodate direct drive by moving some mirrors and adding others to reorient the directions from which beams enter the target chamber. Additional optical equipment would also be needed to smooth the profile of each laser beam.

DOE supports the addition of direct-drive, but to minimize the cost estimate for NIF, the basic design requirement states only that: "Future upgrade to meet the following requirements, specific to direct-drive experiments, shall not be precluded in the baseline NIF design."[36] The requirement goes on to detail specific standards that the direct-drive capability should meet. DOE has not included the cost of purchasing and installing the additional mirrors and other equipment that would be needed for direct-drive in any of its cost estimates for NIF. It does, however, plan on shutting down the facility for about three months one or two years after achieving ignition with indirect-drive in order to install the capability for direct-drive.

In 1996, DOE estimated that "at least $19 million (1997 dollars) should be included in the ICF Program planning around 2006 for direct-drive implementation."[37] We estimate that, with inflation and the delay and overall increase in the NIF Project since 1996, implementation of direct-drive will cost $50 million from 2010–2013.

The Capability to Operate at Additional Frequencies (1ω and 2ω) Would Cost $30 Million

The basic design requirements for NIF state, "The wavelength of the laser pulse delivered to the target shall be 0.35 microns (μm). The design should not preclude delivering 0.53 μm and 1.05 μm wavelength light to the target with reasonable modifications."[38] The cost of such modifications is not in the August 2000 baseline cost estimate, nor has DOE released any estimate for their cost. We estimate that it would cost $30 million to add the capability to operate at additional frequencies beginning in 2014. The weapons physics community would like this capability to perform experiments that cannot be done at the shorter wavelength of the baseline design.

Increasing the Number of Laser Slabs from Sixteen per Beam to Eighteen Per Beam Would Cost $60 million

The designers of the NIF have weighed the advantages of using 16 or 18 glass slabs per laser beam in the design of the facility since the days of the conceptual design. The 18-slab design would provide greater assurance in meeting the design energy per beam and might provide for operating at energies above the design energy. The tradeoff is of course cost. In the current design, the glass slabs, in which the actual lasing takes place, are stacked in two streams of 11 and 5 slabs (referred to as the 11-5 configuration). The 18-slab architecture would be an 11-7 configuration.

The Interim Report of SEAB’s NIF Laser System Task Force recommended that DOE increase the robustness of the NIF design by “utilizing the 11-7 configuration in the new baseline.”[39] This recommendation was softened in the final SEAB Report to “Increase the design robustness where feasible, such as allowing for the 11-7 beamline architecture.”[40] The current baseline plan leaves sufficient space in the beamline infrastructure for the 11-7 architecture. DOE plans to install the first eight beams of the NIF in the 11-5 configuration and decide whether to go to the 11-7 configuration after initial tests of the first eight beams. The August 2000 cost estimate, however, only includes funds for the 11-5 configuration.

DOE would need to purchase and install an additional 384 laser glass slabs to reach the 11-7 configuration. It may also need to install additional flashlamps to power the laser as well as additional capacitors to power the flashlamps. The current baseline estimate for laser glass for the 11-5 configuration is $400 M. We estimate that the additional glass slabs, which represent a 12.5 percent increase, could be procured for an additional 10 percent or $40 million. We also estimate that an additional $20 million would be needed to inspect, test, and install the additional glass and procure and install any additional flashlamps and capacitors that may be needed. This modification would add $60 million to the DOE August 2000 baseline cost estimate for laser glass.

This modification would add $60 million to the DOE August 2000 baseline cost estimate for laser glass.

Enhancing the Use of Other ICF Facilities to Lessen the Impact of the Delay in NIF Would Cost $120 million

In March 2000, the Department of Energy established a NIF Target Physics Program Review Committee to address the impact of current NIF plans on the Stockpile Stewardship Program. The charge to the Committee included a request to, “Review ways of mitigating the impacts of delays, such as expanding the use of other facilities before and during the ramp up phase of the NIF, and minimizing the ‘learning curve’ for use of the NIF.”[41]

That Committee concluded: “A program the utilizes other, high-quality facilities, coupled with a deployment strategy for NIF will allow quality people to be attracted and retained.” It recommended that: “The use of ICF facilities (particularly Omega and Z) [DOE facilities at the University of Rochester and Sandia National Laboratory, respectively] for improving laser-capsule coupling and diagnostic techniques, and other weapons science experiments should be enhanced.”[42]

Should DOE follow this recommendation and increase funding for other ICF facilities, the costs would be directly

Table 2

COSTS FOR ANTICIPATED FUTURE PROJECT ENHANCEMENTS

(Dollars in Millions)

CATEGORY	ESTIMATE OF ADDITIONAL COSTS
PRE–2008 COSTS	
INCREASE NUMBER OF LASER SLABS TO EIGHTEEN PER BEAM	$60
ENHANCE USE OF OTHER ICF FACILITIES	$120
TOTAL	$180
POST–2008 COSTS	
ADDITION OF A SECOND TARGET CHAMBER	$400
FULL CAPABILITY FOR DIRECT-DRIVE EXPERIMENTS	$50
CAPABILITY TO OPERATE AT ADDITIONAL FREQUENCIES	$30
TOTAL	$480

attributable to the delay in NIF and therefore legitimately count as a NIF-related cost. DOE might increase funding for other ICF facilities by $20 million per year from 2003 through 2008, for a total increase of $120 million.

Comparison of Cost Estimates to Build the NIF

As discussed above, DOE's August 2000 baseline estimate of $3.448 billion for the total cost of building the NIF excludes significant categories of project-related costs. If one adds our estimates for "Project-Related Costs Charged to Operating Programs" and "Costs for Future Project Enhancements" through the scheduled completion of the Project in 2008, the total cost to build the NIF and commission it for operation comes to $4.960 billion. An additional $480 million for Project enhancements is likely to be added after completion of the initial Project.

Those estimates provide a full accounting of the direct costs associated with building NIF to DOE's August 2000 baseline schedule and requirements. However, the estimates assume that DOE is able to complete the Project according to the current schedule and that DOE encounters no technical problems in meeting the design requirements that would materially increase the Project cost.

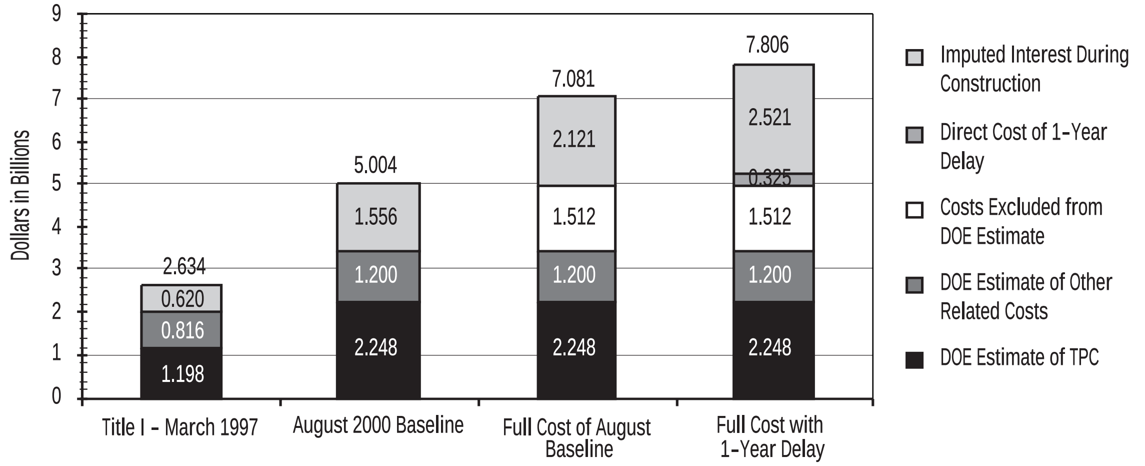
We believe there are technical problems that will require additional spending to address, that will further delay completion of the Project, and that may even prevent DOE from ever meeting all of the requirements of the current design. The potential for such additional cost increases and delays is discussed in subsequent sections of this report, as is the full cost of operating the NIF. In the remainder of this section, we continue to examine the cost of building NIF to DOE's current design and schedule and compare that to previous cost estimates.

Under the current baseline schedule, full operation of the 192-beam NIF is delayed by nearly four years from the previous schedule. One must account for this delay to fairly compare the 1997 schedule and cost estimate with the August 2000 baseline. The full cost of the delay is more than just the increase in the direct costs of construction. For those who believe the NIF would be of some use to Stockpile Stewardship, there would be an opportunity cost in foregoing that use for four years. That cost is difficult to quantify and we do not share that belief in any event.

There is also a financial cost to the delay, because the Government will have invested significant funds in building a facility that will not operate for at least four years beyond the previous plan. We can estimate the financial cost of this delay. We do that by "imputing" an appropriate amount of interest to the funds that the Government is projected to spend on building the facility up to the start of full operations. Since the Government is still paying interest on a sizable national debt, the Government's investment in an expensive facility, such as the NIF, should reflect the interest during construction. This is especially true when one wants to compare two cost estimates and construction schedules in which the length of the construction period differs by as much as four years, because the interest over those four years is substantial.

Figure 7

COMPARISON OF NIF COST ESTIMATES WITH IMPUTED INTEREST



The practice of adding interest during construction to the estimated cost of a capital project is normal practice in the private sector. A Company must calculate its full investment in a facility, including interest, in order to determine the return on its investment needed to profit from building the facility. The Government will not sell the products of the NIF. Nevertheless, it is useful to calculate the Government's full investment in the facility in order to weigh the value of its output against its full cost.[43]

We use the interest rate on 10-year Treasury notes for imputing interest to the cost of building the NIF, because the 10-year period closely approximates the time for building the NIF. We have applied the historical interest rate on 10-year notes from 1996 through 2001 to the total spending through the beginning of each corresponding year and OMB projections of the interest rate to the cumulative spending estimates by year through 2008. When the appropriate interest rates are applied to the Title 1 cost estimate from 1997, it increases from $2.014 billion to $2.634 billion. When interest is imputed to DOE's estimated cost for the August 2000 baseline, it increases from $3.448 billion to $5.004 billion, and when interest is applied to our estimate of the total project-related cost through Project completion in 2008, that increases from $4.960 billion to $7.081 billion. Hence, our estimate of the full cost to build the NIF and commission it for operation, including imputed interest, is nearly three times the corresponding cost estimate from the 1997. It is also worth noting that our estimate of the full cost, with imputed interest, of building the NIF on the current schedule is nearly six times DOE's 1997 estimate of the "Total Project Cost" or TPC for the NIF, which was only $1.198 billion.

Hence, our estimate of the full cost to build the NIF and commission it for operation, including imputed interest, is nearly three times the corresponding cost estimate from the 1997.

These cost comparisons are shown graphically in Figure 7. Also included in Figure 7 is our estimate of the cost of building NIF assuming the Project is delayed by one year from the current schedule. In that case, we estimate that the direct cost would increase by $325 million and the imputed interest by $400 million, bringing the total cost to build the NIF to $7.806 billion. NIF may well be delayed by more than one year.

DOE Underestimates the Operating Costs for the NIF

The cost of building the NIF is only a portion of the total spending commitment, which the Government is making by erecting facility. The cost to operate the facility over its projected 30-year lifetime would greatly exceed the construction costs. DOE takes a narrow view of operating costs, considering only the physical operation and maintenance of the facility. We include the cost of performing and analyzing experiments on the NIF in our cost estimate. Those costs are explained below.

DOE's estimate of the annual operating cost for the NIF from 2009 through 2038 is $145 million in 2001 dollars.[44] The Construction Project Data Sheet for the NIF breaks that sum down into several pieces as follows:

Annual facility operating costs	$38.8 million
Annual facility maintenance/repair costs	$55.8 million
Programmatic operating expenses directly related to the facility	$41.9 million
Construction and equipment related to the programmatic effort	$ 0.4 million
Utility and other costs	$ 8.2 million
TOTAL	$145.1 million

At an inflation rate of three percent per year, the total would increase to $184 million in 2009, which is the year that NIF is scheduled to begin operation. However, that figure is only a fraction of the total operating costs of the NIF, because the DOE estimate of operating costs does not include the full cost of scientists who would use the NIF, the cost of diagnostic equipment for experiments, the full cost of maintaining the final optics assembly, or the cost of laboratory overhead. Those costs are discussed in the following four sections and summarized in Table 3.

the DOE estimate of operating costs does not include the full cost of scientists who would use the NIF, the cost of diagnostic equipment for experiments, the full cost of maintaining the final optics assembly, or the cost of laboratory overhead.

Full Cost of Scientists and Technicians Who Would Use the NIF

According to the Construction Project Data Sheet, the $41.9 million for programmatic operating expenses directly related to the facility, "Includes the LLNL portion of the national ICF Program that is directly related to the use of NIF, but not facility scientific support, which is now included in facility operating costs."[45] The Project Data Sheet does not specify how much is included in the facility operating costs for facility scientific and technical support. In any event, LLNL's ICF program represents only a portion of the programmatic users of the NIF.

DOE's plans call for less than half the shots on the NIF to be dedicated to ICF (either ignition physics or inertial fusion energy).[46] Most of the remaining shots would be for other nuclear weapons-related experiments, with a smaller portion for basic science and technology. DOE's cost estimate does not include funding for the scientists and technicians who perform these non-ICF experiments. In addition, DOE's cost estimate does not include funding for the substantial portion of expected users of the NIF, within and outside of the ICF Program, who would come from DOE laboratories other than LLNL.

Assuming that LLNL employees represent about two-thirds of the NIF users from the ICF program and that the ICF program represents about 45 percent of all DOE users of the NIF, then the DOE figure of $41.9 million for programmatic operating expenses would account for only 30 percent of all programmatic users. Our estimate of the operating expenses for the NIF includes an additional $98 million per year for the 70 percent of the scientific users of the NIF who are excluded from the DOE cost estimate.

Diagnostic Equipment for Experiments

The Construction Project Data Sheet explains that the cost of most diagnostic equipment for experiments is excluded from DOE's estimate of the cost of the NIF *Project*, because it will be funded by the operating programs. As discussed above, we added $175 million to the DOE estimate of the total project cost for the cost of designing and acquiring diagnostic equipment from 1997–2008. The data sheet does not explain why its estimate of $0.4 million for "annual operating costs for construction and equipment related to the programmatic effort" apparently also excludes the cost of diagnostic equipment. Even if a substantial suite of diagnostic equipment were installed before full operations is scheduled to begin in 2009, there would be a continuing demand for more, as technology improves and the types of experiments that are performed on the NIF changes. Our estimate of annual operating costs includes an additional $10 million per year (in 2001 dollars) for diagnostic equipment.

Full Cost of Maintaining the Final Optics Assembly

The final optics assembly consists of a series of optical components that are mounted on the target chamber. It includes: the frequency tripler to convert the laser light from 1.06 μm to 0.35 μm, the final focusing lens, diffraction gratings to shift unconverted light away from the target and perform other functions, a vacuum barrier, and a debris shield to protect the other optical elements from exploding targets. There are a total of 48 final optics assemblies, which each hold the components for four beams. The components of the final optics assembly must withstand the highest intensity laser light (highest fluence) of any of the optical components in the NIF. This high intensity light is expected to cause progressive damage to the final optics, which means that the optical components would have to be replaced periodically. The components most susceptible to damage from high laser fluences are the frequency tripler and the debris shield.

The frequency tripler is comprised of successive crystals of potassium dihydrogen phosphate (KDP) and deuterated potassium dihydrogen phosphate (DKDP). The debris shield and all the other components are made from fused silica.

DOE's estimate of the annual operating expenses for the NIF includes $20 million for maintaining the final optics assembly.[47] This includes the cost of refurbishing and replacing components as needed. It provides for replacing all of the debris shields once per year,[48] replacing the other fused silica components once every two and one-half years, and replacing the KDP and DKDP crystals every two years.[49] DOE is, however, far from having components that can withstand damage for those lengths of time at the desired shot rate, which is 600 shots per year initially (including about 150 at full-power), and double that after a few years.[50]

Scientists have a limited understanding of the damage process. The process is somewhat random and depends in a complex manner on the number of shots, the fluence levels of the shots, and the order in which shots of different fluence levels occur. Therefore, it is difficult to specify exactly how many shots a given component can withstand before it must be replaced. DOE statements about the status of damage resistance reflect this difficulty and are somewhat vague and contradictory. The following are among the more definitive public statements that have been made on the subject:

> If the damage level cannot be raised over the next five years, NIF can operate at full optical output energy for approximately 1/10 the number of planned shots before having to replace the fused silica optics, thus increasing the cost of operating the NIF at full beam energy.[51] And,
>
> The question is: What is the cost of operating NIF at its point design at 8 joules per square centimeter? [i.e., full power] Right now we're at the 50-shot range before we replace the optics now. That means you could do 50 experiments at, you know, full power, full energy, and then replace those optics.[52]

The first quote, when combined with the planned replacement rates cited above, implies that the current state of development would require replacing the debris shields as often as ten times per year and other fused silica components four times per year to achieved the desired full-power shot rate.

The second quote appears to refer to the KDP and DKDP crystals as well as the fused silica optics. It implies a need to replace all of the optics three times per year to achieve the desired full-power shot rate of 150/year. That replacement rate is three times the current plan for the debris shield, six times the current plan for the KDP and DKDP crystals, and seven and one-half times the current plan for other fused silica components.

Under that assumption, the maintenance costs for the final optics would triple to $60 million per year.

Taken together, the two quotes imply that in order to achieved the desired full-power shot rate with components at today's level of damage resistance, all of the final optics on the NIF would have to be replaced six to ten times more often than DOE assumes in its estimate of the maintenance cost. DOE is working to improve the damage resistance of the final optics. As discussed later in this report, however, it is not clear how successful that effort will be. Our estimate of operating costs assumes that DOE improves the damage resistance of components enough that they need only be replaced three times as often as is assumed in the current estimate of operating costs. Under that assumption, the maintenance costs for the final optics would triple to $60 million per year, which would add $40 million (in 2001 dollars) to DOE's estimate of the operating cost of the NIF.

Ours is a conservative estimate. It assumes a substantial improvement in damage resistance by 2009 that has not been demonstrated; it does not include potential future increases in the maintenance costs for the final optics when/if DOE doubles the shot rate as planned; and it accepts DOE's estimate of the cost of the components of the final optics assembly. A review of the August 2000 baseline cost estimate performed by Burns and Roe for DOE's Office of Engineering and Construction Management, casts doubt on that final assumption, stating:

> The Final Optics System is an area filled with unknowns and technical challenges. . . . It is possible that the cost of the Final Optics System could be substantially higher than the Budget.[53]

Laboratory Overhead

DOE's estimate of the operating costs for the NIF of $145 million does not include laboratory overhead. However, when/if funds are appropriated to operate the facility, it would be necessary to pay the overhead charges for general and administrative costs (G & A) that apply to nearly all operating expenses funded at LLNL. In recent years, the G & A rate at LLNL, which would be applicable to NIF, has been about 47 to 49 percent.[54] An additional charge of 6 percent has been applied to operating accounts at LLNL to fund Laboratory Directed Research and Development (LDRD). For our cost estimate, we used a conservative estimate for total overhead charges of 50 percent. Applying a 50 percent overhead rate to the DOE estimate of operating cost for the NIF and to our estimate of additional costs discussed in the preceding three sections, adds $147 million to the annual cost of operating the NIF.

Table 3

OPERATING COSTS FOR THE NIF

(Dollars in millions)

CATEGORY	ESTIMATE OF ADDITIONAL COST	
	2001 DOLLARS	2009 DOLLARS
DOE ESTIMATE PER CONSTRUCTION PROJECT DATA SHEET	145	184
FULL COST OF SCIENTISTS WHO WOULD USE THE NIF	98	124
DIAGNOSTIC EQUIPMENT FOR EXPERIMENTS	10	13
FULL COST OF MAINTAINING THE FINAL OPTICS ASSEMBLY	40	51
LABORATORY OVERHEAD	147	186
TOTAL	440	558

Summary of Estimated Costs of Operating the NIF

Table 3 summarizes our estimate of the operating cost for the NIF. Figures are given in 2001 dollars and 2009 dollars (escalated at 3 percent per year), since that is the scheduled first year of operation.

We can arrive at separate, confirmatory estimates of the total operating costs using two entirely different methods. According to the National

Academy of Sciences (NAS) 1997 review of the NIF, "High-technology facilities usually require between 10 and 13 percent of the Total Project Cost to fund operations each year after the facility is fully operational."[55] Applying those percentages to our estimate of $4.960 billion for the total project-related costs for building and commissioning the NIF, would give an operating cost of $496–645 million. This is presumably in 2009 dollars, since the percentages suggested by the NAS would be applied at the conclusion of the project.

In addition, according the Programmatic Environmental Impact Statement (PEIS) on the Stockpile Stewardship Program, "The total number of jobs (direct plus indirect) during operation [of the NIF] would be 890 at LLNL, 600 at LANL, 620 at NTS, and 670 at SNL.[56] That gives a grand total of 2780 jobs. Many of those jobs would be scientists and engineers. Assuming an average fully-loaded salary of $130,000 per year, that would provide an estimate of $361 million for salaries alone for operating the NIF. Utilities and materials costs would bring that figure to the vicinity of $450 million per year in 2001 dollars.

> The full cost of operating the NIF from 2009 through 2038. . . comes to a staggering $26.5 billion.

DOE projects a 30-year operating life for the NIF. We are skeptical that the facility could be operated productively for nearly that long. Nevertheless, we have used DOE's 30-year lifetime in our full life cycle cost estimates. Using the DOE estimate of $145 million (2001 dollars) inflated at 3 percent per year, the total operating cost of the NIF would come to $8.7 billion over the 30-year period from 2009 through 2038. The full cost of operating the NIF from 2009 through 2038, based on our estimate of operating costs of $440 million in 2001 dollars, inflated at three percent per year, comes to a staggering $26.5 billion.

Total Cost for Building and Operating The NIF

If one combines DOE's estimate of the project-related cost of building the NIF ($3.5 billion) and its projected 30-year operating cost ($8.7 billion), the total is $12.2 billion. Our estimate consists of the total project-related costs of building the NIF ($5.0 billion), the cost of future upgrades to the Project ($0.5 billion), operating costs from 2009 through 2038 ($26.5 billion), and programmatic operating costs from 2004 through 2008 ($0.5 billion)[57], for a total of $32.4 billion. Figure 8 compares our estimate of the full cost of building and operating the NIF in accord with DOE's August 2000 schedule to DOE's estimate of those costs.

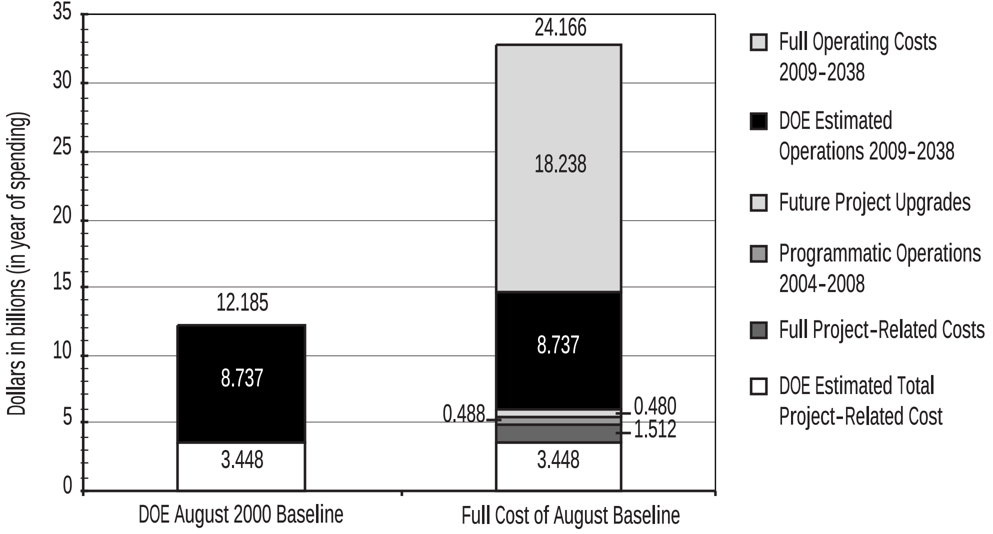
Our estimate of the full discounted future cost of building and operating the NIF is $9.9 billion (2001 dollars). This means that, canceling the NIF this year would save $9.9 billion in 2001 dollars.

The numbers in the previous paragraph are expressed in "as-spent" dollars. That is dollars that are valued in the year in which they have been or are projected to be expended. That method provides the most intuitive estimate of what total spending on the project will be. It is useful, however to also calculate the decision cost in today's dollars of proceeding with or canceling the NIF. To do that, one should look only at the future costs (from 2002 forward) and should discount those costs to the present.[58] Using a discount rate of 6 percent per year, which is appropriate for Government spending, the discounted future cost of building and operating the NIF using DOE's August 2000 cost estimate is $3.7 billion (2001 dollars). Our estimate of the full discounted future cost of building and operating the NIF is $9.9 billion (2001 dollars). This means that, canceling the NIF this year would save $9.9 billion in 2001 dollars.

Figure 8

TOTAL COST OF BUILDING AND OPERATING THE NIF

(in "As Spent" Dollars)



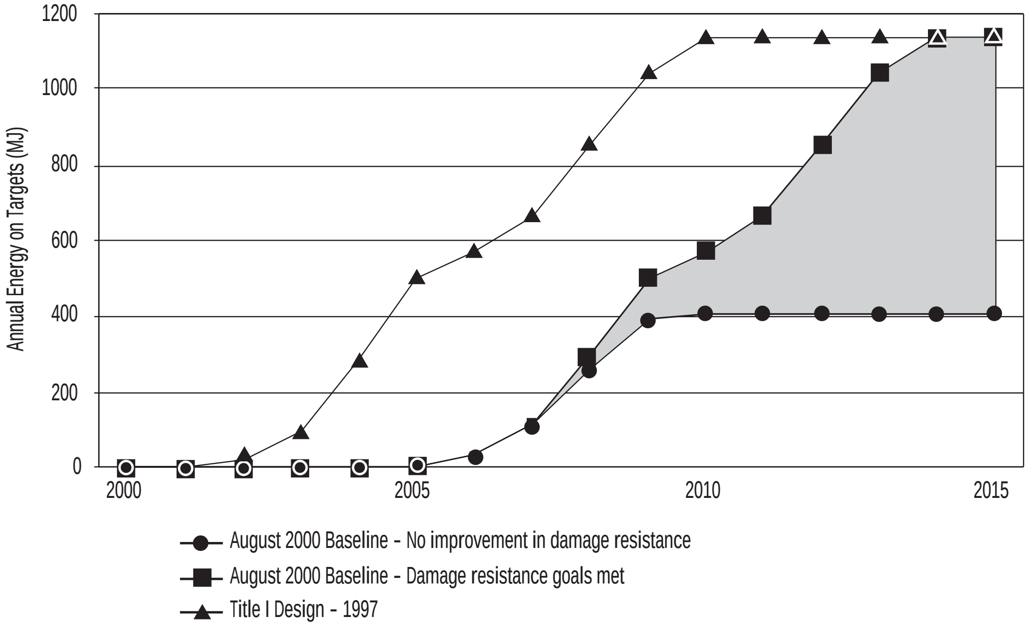
Cost Effectiveness of NIF Operations

In addition to delaying the Project by four years and nearly tripling its cost estimate in August 2000, DOE also revealed that it had been unable to develop components for the final optics assembly that could withstand damage from the high laser fluences of full-energy shots for anywhere near the number of shots desired. The Department, therefore, plans to limit NIF operations to one-half of the design energy on all beams until at least mid-2007. NIF supporters hope they will be able to development more damage resistant final optics by that date, but there is little evidence that the full design requirements for damage resistance can be met. It appears likely that the number of full energy shots on the NIF will remain below planned levels for some time.

This triple whammy of increased cost, delayed schedule, and reduced operating energies dramatically reduces the value or cost effectiveness of the NIF even to its supporters. Figure 9 shows our estimate of the annual energy output (on targets) of the NIF for the initial schedule established in 1997 during the Title 1 Design and for the August 2000 baseline under two assumptions. In one, we assume that DOE is sufficiently successful in improving the damage resistance of the final optics assembly that it can meet its desired shot rate for full power and other shots, so long as it changes the optics three times per year. In the other, we assume that DOE makes no further improvement from the current state of damage resistance and limits replacement of the optics to three times per year for cost reasons. In that case, the number of full power shots would be significantly limited. Should NIF be completed, the actual output will most likely be

Figure 9

POTENTIAL OUTPUT FROM THE NIF



between these two limits. Additional assumptions and sources of information used in preparing Figure 9 are provided in the endnotes.[59]

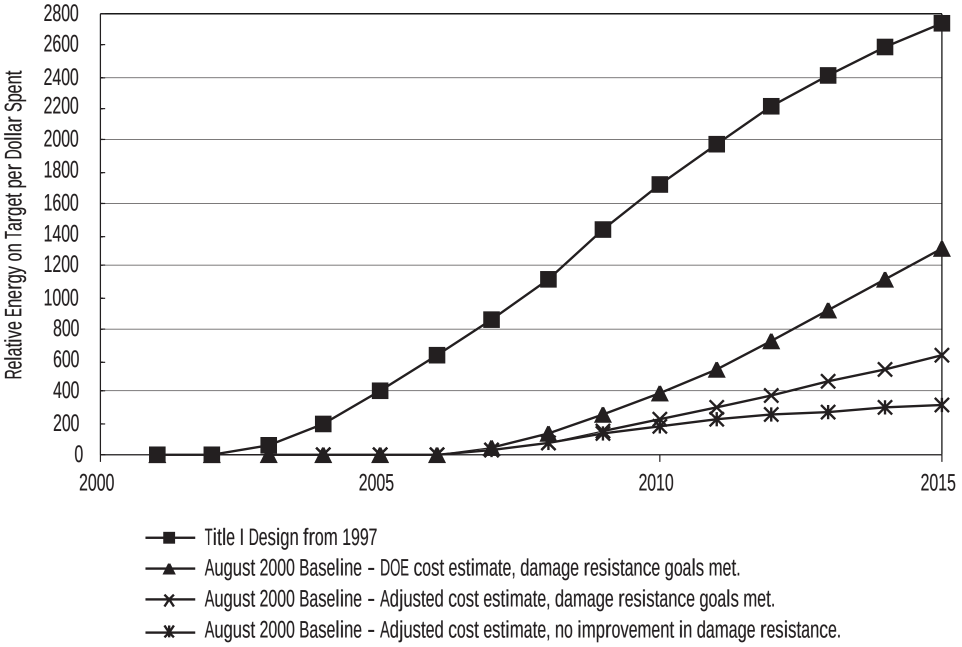
The total energy delivered to targets is not a perfect measure of the value of the NIF. Some experiments can be done at lower energy levels. Nevertheless, it is not a bad proxy. The primary reason for building the NIF was to achieve ignition, which, if possible, would require numerous shots at or near full energy. Furthermore, the uniqueness of the NIF is in its ability to focus large amounts of energy on targets over brief periods. The extent to which NIF fails to deliver as much energy on targets as planned is a reasonable measure of the extent to which it will have missed meeting its promise. Figure 9 shows that the output from the NIF will remain below the levels anticipated by the Title 1 Design until at least 2014, and the output may never reach the original expectations of the Title 1 Design, which was the basis for Congressional approval of the Project.

We have plotted the projected cost effectiveness of the NIF by combining the information in Figure 9 with the construction and operating cost estimates discussed above. Cost effectiveness is defined here as the total amount of spending on the Project through a particular year divided by the total amount of energy delivered to targets through that year. Figure 10 is a graph of the cost effectiveness of the NIF over time for four different cases.

By comparing the top two lines in this figure, one can see that, even using DOE's cost estimate and assuming DOE is able to meet the damage resistance requirements for the final optics, the NIF is expected to provide less than one-quarter the output per dollar spent through 2010 as it was to have under the

Figure 10

COST EFFECTIVENESS OF THE NIF



Title 1 Design. Over the long term, it will never exceed one-half the cost effectiveness expected in 1997.

This triple whammy of increased cost, delayed schedule, and reduced operating energies dramatically reduces the value or cost effectiveness of the NIF even to its supporters.

Comparing the first and third lines from the top, one can see that based on our estimate of the total cost of the NIF, if DOE is fully able to meet the requirements for damage resistance, the NIF will ultimately reach only one-quarter the cost effectiveness expected in 1997. Finally, comparing the top and bottom lines in Figure 10, one can see that based on our cost estimate, if DOE is unable to improve the damage resistance of the final optics and NIF is completed and operated anyway, it will deliver less than one-ninth the energy per dollar spent that was previously expected.

It is important to note that Figure 10 assumes that the NIF is completed in accordance with the schedule set forth in the August 2000 baseline *without delay*. In addition, it assumes that all technical requirements are fully met, except for the possibility of not meeting the damage resistance requirements for the final optics. Additional delays or technical problems would further reduce its cost effectiveness. The potential for such problems and delays is discussed in the next section.

Technical Issues and Other Problems are Likely to Cause Further Delays and Cost Overruns

The NIF is one of the most complex, technically challenging projects ever undertaken by the Department of Energy. Such projects by their very nature are highly subject to delays and cost overruns. The U.S. General Accounting Office reviewed DOE's record for completing major projects on time and on budget in 1996 and found:

> From 1980 through 1996, the Department of Energy (DOE) conducted 80 projects that it designated as major system acquisitions. DOE has completed 15 of these projects — most of them behind schedule and over budget. Three of the completed projects have yet to be used for their intended purpose. Thirty-one other projects were terminated before completion, after expenditures of more than $10 billion. The remaining 34 projects are ongoing. Cost overruns and "schedule slippages" continue to plague many of these ongoing projects.[60]

Therefore, it should not be surprising that NIF has experienced cost overruns and schedule delays. More than seven years remain before the NIF is scheduled for completion. Numerous technical challenges must still be resolved. DOE's past record almost guarantees that there will be more schedule delays and cost overruns in the future.

The conventional wisdom, supported by the SEAB NIF Task Force and the now discredited Carlson-Lehman Review, holds that the past cost overruns and schedule delays in the NIF Project were the result of management weaknesses and oversight failures. That easily reached conclusion hides some underlying reasons for the problems, including:

- Overconfidence on the part of the scientists and engineers associated with the Project, leading them to believe they could stretch the limits of unproven technologies to satisfy challenging design problems, and
- Strong political pressure on Project staff to lowball cost estimates and hide emerging problems to present the Project in its most favorable light to decision makers in the Administration and the Congress.

The major reason for the cost overruns and schedule delays in the NIF was that the technical team was overconfident in judging its ability to solve difficult problems including assembling a laser with stringent cleanliness requirements in a cramped and dirty environment.

Since the problems with NIF were first revealed, DOE has made numerous management changes in the Project in a showy response to the Congress, which gives the appearance that they are doing something. While management shortcomings were evident in that high level Project managers covered up technical problems, the major reason for the cost overruns and schedule delays in the NIF was that the technical team was overconfident in judging its ability to solve difficult problems including assembling a laser with stringent cleanliness requirements in a cramped and dirty environment. Slow progress on a host of other technical issues also contributed to cost increases. There has been no suggestion that these technical issues were mismanaged, only that their difficulty was underestimated and they were not publicly acknowledged sooner. The primary reasons that the problems were not acknowledged sooner was a fear among project managers to let the Administration and the Congress know about potential problems and a belief in their technical ability to solve the problems.

The DOE response was much like the owner of a baseball team firing the manager of a losing franchise. True, the manager is ultimately responsible for everything that takes place on the field. However, a new manager alone cannot guarantee victory. Fundamental changes may be necessary. The problems with NIF may well go deeper than the people involved and may require fundamental changes in the scope of the Project. However, except for stretching out the schedule and increasing R & D funds for some of the most perplexing unresolved technical problems, DOE has made no scope changes to any of the final technical requirements for the NIF. According to DOE, the 22-page NIF Functional Requirements and Primary Criteria document,[61] which established the performance requirements of all the systems in the NIF, remains unchanged from 1997.[62] We doubt that the new Project Team will be able to meet all of the original requirements, on schedule, any more than the old Project Team could.

The successful scientists and engineers who rise to leadership positions in managing projects like the NIF tend to be optimists. They generally have histories of solving difficult problems and believe they can continue to do so. From the beginnings of the NIF Project, several review teams have noted the numerous technical challenges facing the Project. However, based on the generally optimistic briefings they receive from Project scientists and engineers,[63] they consistently issued positive sounding statements predicting that Project goals can be met. The positive statements by review teams may also have resulted from conflicts of interest among the members of some of those teams.[64]

The 1997 review of the NIF by the National Academy of Sciences noted the challenges stating:

> 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 computation experience. . . . Several technical issues should be pursued in parallel with NIF construction.

Nevertheless, it concluded optimistically,

> In sum, the committee believes that the NIF can be delivered to specifications with the stated TPC, as augmented by LLNL-projected operating funds,. . . there are no identifiable "show stoppers."[65]

Similarly, DOE's 1997 so-called "Independent Cost Estimate of the Title 1 Design" noted risks, but did not predict they would lead to cost overruns, stating:

> The Project has lots of risks, particularly in optics, but LLNL appears to be managing the risks through backup plans, by facilitizing more than one vendor in a particular area, and by developing prototypes. The commitment and dedication of the people will be the reason that this Project is a success.[66]

The huge cost increase of August 2000 revealed how misplaced the optimism of these reviewers was. The new set of reviews that affirmed DOE's August 2000 rebaseline continued the familiar refrain that while significant technical challenges remain, they are optimistic that the challenges will be overcome.

The Technology Review Group of the NIF Council concluded:

> . . . significant progress has been made in all eight of the key technology areas. However, achieving the full NIF performance requires completion of technology development objectives in all of these areas. Progress toward these objectives continues to expose technical challenges that require continuing investment in technology development. This process is typical of all advanced technology development projects that are predicated on significant advances in the state of the art. While much work remains to be done, and many remedial activities both technical and managerial need to be undertaken, we are confident that with the help of recommendations contained in this report
>
> **NIF can reach its original performance goals although with some delay and at higher cost than originally projected.** [Emphasis in original][67]

The huge cost increase of August 2000 revealed how misplaced the optimism of these reviewers was. . . . The current set of reviews has similar conflict of interest problems to those of the earlier NIF reviews.

The SEAB NIF Task Force stated in its interim report that:

> NIF is a very difficult engineering challenge and further technical problems should be expected. . . . Small optics is an example where the risk of not reaching full performance of the beamline quality is high. . . Cleanliness is another example. . . Installation of the beampath elements is a third example.[68]

Nevertheless, in its final report nine months later, it concluded

> The NIF Task Force considers important the issues of optical damage, laser glass procurement, KDP crystal growth and fabrication, small optics, and NIF as an operating laser system. However, based on the Task Force's review these issues are capable of being resolved with adequate research and development effort. Accordingly there are no technical problems related to optics that in principle will prevent the NIF laser from operating as a partial system initially and a 192-beam laser system in completed configuration.[69]

The current set of reviews has similar conflict of interest problems to those of the earlier NIF reviews. There is little difference between the assurances given by DOE and its recent reviewers and those given in 1997 and before that the remaining technical obstacles for completing the NIF can be resolved on schedule and within budget. Scientists remain optimistic, but DOE and the larger scientific community have been working on key issues related to many of these problems for years and, in some cases for decades. Progress has been made on the NIF's most difficult technical challenges, but further advances are becoming increasingly more difficult. Until the technical requirements for all NIF systems and components have been demonstrated, there remains significant potential for further Project delays and cost overruns.

We are not alone in this belief. In a November 25, 2000 letter to DOE Secretary Richardson, three members of the SEAB NIF Task Force dissented from the conclusions of the final report and stated:

> . . . there is the question whether the laser will be able to meet its performance specifications, and be useful for the study of fusion ignition and other non-ignition weapons science. We cannot endorse "completion" of a $4 billion project irrespective of its ability to perform its intended mission. . . .
>
> We have recommended that SEAB adopt the explicit recommendation that continuation of this construction project be contingent on a demonstration that the 8-beam "performance bundle" meets the technical specifications required to conduct fusion ignition and other stockpile stewardship experiments.[70]

Several of the remaining technical issues are summarized below. Experience shows there is a high probability that one or more of them will prove to be more difficult to resolve than DOE currently anticipates and could result in extensive delay of the Project. We estimate that a one-year delay in completing the Project would add about $325 million to the direct project-related costs and an additional $400 million in imputed interest. Unresolved technical problems could delay the project much longer than one year.

Laser System Performance

The most basic technical issues regarding the NIF laser are:

- Whether the laser system will be able to meet is performance specifications for energy and power; and
- Whether DOE will be able to sufficiently focus the light from the 40-cm (16-inch) diameter lasers into the 0.06-cm (0.025-inch) spot size it believes is necessary for uniform heating of the hohlraums and other experiments.

No one expects a large laser to reach its full power the first time it is turned on. DOE plans to start up laser beams at well below their design energy and power and to improve their performance over time. The August 2000 baseline schedule, however, does not leave sufficient time for the Project Team to operate the earliest commissioned beams and demonstrate that they can reach full power operation and meet the focusing requirements before DOE plans to give it the go ahead to complete the facility

Project Team scientists at Los Alamos National Laboratory are concerned about this problem. Early this year, they proposed an additional milestone for the NIF Project to demonstrate laser beam system performance. The new milestone requires that after commissioning the first 48 beams (scheduled for June 2006) the Project must demonstrate it can meet 75 percent of the full energy and power requirements for individual laser beams and can focus 75 percent of that reduced energy into the required spot size.[71] The full performance requirement is that 100 percent of the beam be focused through such a pinhole. Thus, two full years after first light is scheduled from the initial eight beams in June 2004, DOE will require only that some beams can achieve 75 percent of the key energy, power, and focusing requirements.

This new milestone is insufficient to guarantee that the NIF will be able to reach its full performance. With only 75 percent of the required energy in the lasers and 75 percent of that focused on targets, the NIF would be able to focus only 0.75 x 0.75 = 0.5625 or just over 56 percent of the required energy on target. If the NIF project cannot meet this new milestone, presumably the Project will be delayed while it works to improve the laser performance. Even if the Project meets this milestone, there will be no assurance that future improvements will allow the system to operate at full power and energy and to focus its beams within a small enough spot size to adequately irradiate hohlraums. Whether the laser system can reach its full energy and power and meet its focusing requirements will remain unknown for some time.

With only 75 percent of the required energy in the lasers and 75 percent of that focused on targets, the NIF would be able to focus only 0.75 x 0.75 = 0.5625 or just over 56 percent of the required energy on target.

Laser Damage to the Final Optics

The large final optics, through which the laser light must pass just before entering the target chamber, are subject to the highest laser fluences of any of the components of the laser. As discussed above, this high intensity light causes progressive damage to the components of the final optics and they will have to be replaced periodically. DOE has not yet demonstrated it can produce components with sufficient damage resistance to allow it to operate the NIF at full energy more than sporadically, even if the laser is capable of reaching full energy.

DOE and the larger scientific community have been working for many years to improve materials resistance to damage from high laser fluences. Substantial progress has been made over the past decades, but it is not clear that further advances are possible. The following quotes from recent reviews of the NIF provide some insight into the difficulty in making further improvements:

> . . . optical damage is statistical in nature and there is no guarantee that continued improvements can be counted upon to increase the optical damage limit.[72]
>
> The type of catastrophic damage being observed on fused silica at high fluence in a vacuum fundamentally calls into question whether fused silica can ever go the distance to reliable operation at full NIF fluence or above. . . . The proper solution is presently unknown. [73]
>
> We recommend that a materials R & D effort be undertaken to develop some better materials and coatings for operation at [full energy]. . . The materials should be developed with an eye towards replacing or protecting the silica optical elements. . . It is our considered opinion that this will prove necessary if reliable and acceptable cost operation is to be achieved.[74]

LLNL acknowledges it may not meet the NIF design requirements for damage resistance to the final optics, but claims that would only affect the level of operating costs and does not threaten timely completion of the Project.[75] Our cost estimate includes an increase of $40 million per year (in 2001 dollars) for replacing the final optics more frequently than originally planned (see above). However, even that estimate assumes that DOE will achieve a factor of three improvement in damage resistance at high fluences to fused silica and to DKDP crystals over what has been demonstrated thus far. If DOE is unable to make any progress in improving the damage resistance at high fluences of the final optics, the NIF operating costs could increase by another $100 million or more per year.

DOE is sufficiently concerned about this problem that it recently added a new performance milestone to the NIF Project baseline to use "data and operations models developed during early deployment, and information gathered during commissioning of the first 48 beams [to] project ultimate NIF laser system shot-rate and associate operating costs."[76] The first 48 beams are not scheduled to be commissioned until June 2006, so this milestone cannot be met before then. It is not clear what DOE would do at that point if there have not been significant improvements in damage resistance at high fluence. Faced with the prospect of dramatically increased operating costs, DOE might decide either to delay completion of the Project, while it conducts additional R & D, or to severely limit the high energy operations of the laser.

Anti-Reflective Optical Coatings

The damage to optical components of the NIF from high laser fluences, discussed above, is attributable to properties of the underlying materials of the optics and how they are finished and polished. DOE has also encountered damage-related problems attributable to anti-reflective coatings that are applied to the optical components. This problem affects primarily the coatings on KDP crystals and the diffraction grating in the final optics.

When light passes through a transparent material, some of it is reflected backwards at the surface where the light exits. Eyeglass wearers are familiar with this annoying reflection. This reflection can be reduced by coating the surface of the glass with appropriate chemicals. In the case of the NIF, anti-reflective coatings are needed to keep the laser light moving forward and prevent excessive losses from the beam. However, during tests of the "sol gel" coating, which has traditionally been applied to optical components to reduce reflections, NIF Project scientists found that etched pits formed on the surface of the materials due to water vapor absorption.[77] These etched pits grow rapidly when exposed to the high laser fluences of the NIF. This problem could limit the number of shots that DOE might be able to perform on NIF before it has to refinish or replace optical components even more severely than the damage mechanisms that were discussed above.

DOE is performing R & D to solve this problem, but has not yet found a workable solution. If no anti-reflection coatings are applied, excessive amounts of laser light will be lost to reflection and the NIF beam lines will be able to produce only a small fraction of their design energy.

Finishing and Polishing KDP and DKDP Crystals

Quite apart from the question of resistance to damage from high laser fluences, DOE has not yet even demonstrated that it can successfully fabricate finished KDP and DKDP crystals that meet all of their other design requirements. The faces of the crystals must be cut and polished to meet extremely stringent specifications of flatness, waviness and roughness that are difficult to meet in such large crystals. Flatness, waviness, and roughness refer to variations in surface heights over different length scales. For the shortest length scale, the surface smoothness must vary by no more than 30 Angstroms or about ten layers of atoms. Over distances of a few inches, the surface must be flat to within 3 µm (1/10,000 of an inch). In addition, the cut faces must be precisely oriented with respect to the axes of the crystal. If these requirements are not met, the conversion efficiency of the frequency doublers and triplers would be reduced and NIF might not be able to get sufficient energy at the correct wavelength on targets to achieve ignition.

Quite apart from the question of resistance to damage from high laser fluences, DOE has not yet even demonstrated that it can successfully fabricate finished KDP and DKDP crystals that meet all of their other design requirements.

Several diamond polishing machines and sophisticated metering instruments are needed to perform the final finishing. None of the equipment used on the Nova laser could meet the more stringent requirements for the NIF's crystals.[78] LLNL plans to do the final finishing of the KDP and DKDP crystals in house. While rough-cut crystals have been delivered to LLNL by outside vendors, LLNL is still developing and testing the machines it will need for the final finishing. The machines that will be used to provide the large-scale flatness appear able to meet the specifications. However, LLNL is having problems with the final finishing machine that was designed and fabricated by the Moore Tool Company. The Moore Final Finishing Machine is to apply the final polish to the surface of the crystals to meet the very stringent smoothness requirements, but LLNL has not yet been able to demonstrate that it can meet the specifications.[79]

The most difficult task in finishing the crystals is obtaining the precise orientation required. The cut faces of the KDP and DKDP crystals must be aligned to their internal crystalline axes within fifteen microradians, or less than one-thousandth of a degree. That is about the angle between lines drawn to the top and bottom of the period of this sentence from a distance of 150 yards. Tests on Beamlet in 1997 revealed that in even the best quality crystals, the orientation varied over the length of the crystal, making the orientation process even more challenging. LLNL is developing a Crystal Alignment Test System (CATS) that it hopes will provide the metering needed to properly align the angles across the entire crystal.[80] Until that machine is built and tested, LLNL will not know whether it can meet the specifications for orienting the crystals.

The Carlson-Lehman Review found that, "Issues remain on DKDP fabrication. . . " and that "Current planning is for a single source for shaping and finishing of all KDP and DKDP crystals. Thus, there is the possibility of a single-point failure for the crystal components. This is a holdover from the extreme fiscal constraints of the past and should not be tolerated in the NIF rebaseline."[81] As of today, LLNL still plans to do the final finishing of the KDP and DKDP crystals in house with machines that have not yet been fully proven.

Target Fabrication

DOE believes that it has several target capsule designs, which could ignite at or slightly below the design energy of the NIF. However, it has not demonstrated that it can fabricate capsules, which meet the specifications of these designs. The most promising target designs are all cryogenic targets. This means that the deuterium and tritium fuel must be maintained at extremely low temperatures so they solidify on the inside surface of the target. The critical aspect of targets, which makes them difficult to fabricate, is that they must have extremely smooth outer surfaces and smooth inner surfaces on both the ablator material and the solid layer of tritium and deuterium. DOE has demonstrated a method for producing sufficiently smooth deuterium-tritium fuel layers. They have not yet demonstrated sufficient smoothness of the ablator materials.

The original LLNL ignition target design had a plastic ablator surrounding the fusion fuel. The plastic ablator design was later abandoned because further calculations at LLNL showed that even small amounts of surface roughness would cause the plastic to mix with the fusion fuel as the target imploded. This mixing would prevent ignition. The next idea for an ignition target was to use beryllium as the ablator material. Since the ablation rate is higher for beryllium than plastic, a little more roughness can be tolerated before the rate of mixing of the ablator and the fusion fuel becomes intolerable. However, beryllium targets are much more difficult to fabricate than plastic targets. Plastic forms somewhat smooth hollow spheres of the appropriate size when drops of molten material are allowed to cool as they fall through the air. Fabrication of beryllium targets requires machining operations and may require welding together of hemispheres, which is very challenging to do while maintaining the appropriate smoothness and sphericity. DOE is once again looking at its original designs for plastic ablators, along with a third type of ablator material, polymide, which is another type of plastic. DOE is simultaneously pursuing target designs of all three materials, because it has not been able to meet the fabrication requirements for any of them. This situation still exists after DOE has spent half a billion dollars over several years trying to design NIF targets that can be fabricated.

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Beampath Integration, Assembly and Cleanliness

The NIF Project Team must meet extremely high standards of cleanliness, while assembling and installing the laser system in a cramped and convoluted infrastructure housed in a dirty Laser and Target Area Building (LTAB). DOE underestimated how difficult this task would be. The need to accommodate fundamental changes in how the laser system would be installed and assembled were the primary reason that the August 2000 baseline resulted in a four-year delay and large cost increase in the Project.

The LTAB, which is virtually completed and cannot be easily modified, is essentially a class 100,000 clean facility. That means it can have as many as 100,000 particles of dust per cubic foot. The laser beampath must be clean to class 1, i.e. one particle of dust per cubic foot. In order to insert the components of the laser into its support structure, DOE will have to protect each component, and the opening into which it is fit, from contamination by the surrounding environment while the installation is taking place. In some cases, this will require building a temporary structure to make each connection. In all, approximately 6,000 clean connections compatible with a class-1 beampath environment must be made. This task is made more challenging by the tight quarters of the LTAB, which was designed to be as small as possible to save money.

Despite these challenges, the SEAB NIF Task Force concluded that:

> NIF is being constructed without adequate prototyping, but it is not appropriate to halt further work to construct a prototype. Instead, the assembly and satisfactory operation of the first bundle should be considered a prototyping activity. It is imperative to allow adequate prototyping-level resources and to reserve adequate time in the Project schedule for the first bundle to be used as a learning vehicle for the remaining bundle installations.[82]

The August 2000 baseline allows approximately 12 months for installing the first bundle. DOE believes this is sufficient to resolve any problems and make adjustments, as needed, before installing the remaining bundles. The scheduled time allotted to install the remaining 23 bundles averages about one month per bundle. Making adjustments in the process will be difficult, because under the current schedule the entire infrastructure for all 24 laser bundles is to be completed before the optics for the first bundle is installed and commissioned. Such a plan greatly increases the difficulty in incorporating operational learning experience from the first bundle into the infrastructure design. Assembling the laser infrastructure and installing the optics is on the critical path for completing the Project. DOE recently selected a new contractor to coordinate this task, which has already begun. Beampath assembly is scheduled to continue until mid-2006. Even with the lengthened schedule, this task is challenging. Any slippage in this activity will further delay the Project. The first bundle is scheduled to be installed and commissioned in October 2004. The potential for significant delay will remain well after that date, until DOE has successfully demonstrated that it can reduce the time needed for installing subsequent bundles to one month. If DOE cannot reduce the installation time to one month per bundle, the Project would be delayed and the cost would increase.

Operations and Control Systems

The laser control systems for the NIF align the laser beams, diagnose the beams, and control the shape of the wavefront of each of the 192 laser beams. This is an immense challenge that will require computerized monitoring and control of approximately 60,000 points for every laser shot[83], including simultaneous operation of 12,000 motors and actuators, 700 cameras and other detectors, 1400 alignment references, 825 charge coupled device (CCD) cameras, 250 photodiodes, and 192 wavefront sensors and deformable mirrors.[84]

> The “Beamlet” test laser, which was a near-prototype of a single beam for the NIF, suffered two catastrophic failures of optics at vacuum/air interfaces. …The NIF operating schedule assumes that there will be no such accidents over the 30-year operating life of the laser.

Following each laser shot, the optical elements within the beamline will need to be assessed for their readiness for the next shot. This is particularly important for optical elements that form a vacuum barrier, since they must withstand the stress associated with the air to vacuum interface. The “Beamlet” test laser, which was a near-prototype of a single beam for the NIF, suffered two catastrophic failures of optics at vacuum/air interfaces. In each accident, numerous optical components were damaged or destroyed and the system was shut down for several weeks. The NIF operating schedule assumes that there will be no such accidents over the 30-year operating life of the laser. That will require a flawless control system. Given the record of the Beamlet, this appears to be exceedingly optimistic.

It will be impossible to fully test the NIF operations and control systems until the full 192-beam system is complete. This presents a significant potential for problems to occur that could delay full commissioning of the NIF very near to the end of the Project, when delay is most costly. According to the SEAB NIF Task Force, “The diagnostics related to operating NIF as a laser system is the least mature element of the NIF program at this time.[85]

Laser Glass

The NIF laser requires over 3,000 high purity neodymium glass slabs, which each weigh about 150 pounds. DOE has been working with two vendors to demonstrate that they can achieve the high purity requirements using a new “continuous melt” process that is necessary to produce the desired quantity of glass in a timely and cost effective manner. The August baseline includes $400 million for glass procurement with a $50 million cost contingency.

The first batches of full-sized NIF amplifier glass delivered were found to be below specifications for a number of reasons. They contained platinum inclusions and high water content and had volume inhomogeneities and surface ripples. The platinum inclusions and water content were the greatest concern, as small volume inhomogeneities and surface ripples can be corrected for by adding an extra polishing step. According to DOE, the increased cost of the additional polishing could be accommodated within the contingency funds for glass procurement.

Pilot runs completed in late 1999 met the specifications for platinum, but still had high water content. A second pilot run at one of the vendors was able to reduce the water content to meet the specifications. That run, however, was much shorter than the required production runs, which are to last about one-year. Before DOE can be sure that the glassmakers can meet all specifications, each vendor must successfully complete a full production run. As of early 2001, that had not occurred.[86]

The Carlson-Lehman Report claimed, “the high yield production of laser glass meeting all specifications for damage and laser quality has been achieved.”[87] That conclusion was premature, since the full-scale production runs had not been completed. Since the production of laser glass is such a large part of the NIF cost, even a small problem here could result in a significant cost increase.

In addition to the technical risks that sufficient laser glass meeting the NIF specifications will not be available on time, there is also a political risk that sufficient glass may not be available. Earlier this year, Japanese glassmaker, Hoya Corporation, with whom DOE has contracted to supply half of the laser glass for the NIF, suspended shipments of glass slabs to DOE. The suspension was in response to pressure from Japanese peace groups and elected officials, who criticized Hoya for helping the United States maintain and improve its nuclear weapons. The groups charged that Hoya was failing to serve its social responsibility as a company in a country that suffered from atomic bombing. On March 28, 2001, Hoya announced it plans to resume shipments, claiming LLNL has assured them that the glass will not lead to new nuclear weapons development. One month later, however, as this report went to press, shipments had yet not resumed. This incident is far from over, as a coalition of Japanese antinuclear and peace organization has indicated their intention of boycotting Hoya products if it goes ahead with the shipments. If Hoya does not supply a substantial portion of the laser glass, it is unlikely that the other supplier, Schott Glass Technologies Inc. of Pennsylvania, could meet the full requirements for the NIF, without significant delay in the Project.

Amplifier Gain

Several technical risks could reduce the gain of the NIF amplifiers from that needed to achieve the design energy. They include:

- Thin laser glass
- Degradation of the anti-reflection coatings on the blast shields
- Contaminants in the laser glass
- Reduced flashlamp reflector efficiency, and
- Degradation of the power conditioning equipment[88]

According to the Technology Resource Group of the NIF Council, also known as the Emmett Group:

> The gain data, when combined with a numerical model of the actual NIF amplifier, indicates that a gain of 5.1 +/- 0.1 %/cm should be achieved. This measurement and calculation was with very dry glass, new silver reflectors, new clean blast shields with good coatings, and new flashlamps. The NIF specification is 5.0 %/cm during system operation. Thus, it is not clear that there is any gain margin under the most optimal conditions, and that if there is any gain margin at all, the water in real NIF glass will eliminate it.[89]

That Group recommended increasing the number of laser glass slabs from 16 to 18 per beam to provide additional margin. The SEAB NIF Task Force made the same recommendation. The August baseline design provides for leaving sufficient space for the additional glass slabs, but does not include the cost of procuring or installing them. Our cost estimate adds $60 million to provide the additional laser glass that is likely to be needed for sufficient amplifier gain.

Target Area Systems — Cryogenic Positioner and Diagnostics for Experiments

DOE has just begun the challenging design of the crucial Cryogenic Target Positioning System. In addition, design and procurement of most of the highly sophisticated diagnostic equipment needed to take data on experiments has not yet begun. These key systems in the target area of the NIF are funded and managed outside of the overall Project. The cryogenic positioner must insert, align and hold the delicate targets steady to within 50 µm (about 0.002 inches) inside the 33-foot diameter chamber. It must do this without blocking the paths from any of the 192 laser beams or the view to the numerous types of diagnostic equipment, all the while maintaining the targets at a temperature of less than 20 degrees Celsius above absolute zero.

Since these target area systems are funded outside of the Project, it is difficult to coordinate their design and installation with installation of Project-funded equipment in the target area, including the 48 final optics assemblies, power and vacuum equipment, equipment for cleaning the chamber after high power shots, and other utilities that are needed. It is likely that conflicts may arise between different subsystems that could delay the overall Project. The Burns and Roe review of the August 2000 baseline found that:

> The target area is extremely congested and a large number of components need to be precisely installed and supported. It is not apparent that this is feasible within the constraints of the schedule and budget currently in place.[90]

DOE has not yet demonstrated that it will be able to design and build a cryogenic target positioner, which can meet the stringent design requirements. Without this crucial piece of equipment, ignition would be impossible.

Conclusions

We have documented a continuing pattern of increasing cost and declining performance expectations for the National Ignition Facility (NIF). In addition, we have highlighted several challenging technical problems, which DOE has not yet resolved. At a minimum, one or more of these problems could cause additional schedule delays and cost increases. If they are not resolved, the NIF laser may never operate at its design energy or may do so for a very restricted number of experiments. Furthermore, the Project may not meet its most important scientific goal — ignition of fusion targets.

In August 2000, DOE increased its estimate of the cost of building and commissioning the NIF from $1.198 billion to $3.448 billion and added four years to the schedule for completing the 192-beam facility. The current DOE estimate still excludes $1.332 billion in project-related spending, which should also be counted as part of the cost of building and commissioning NIF. We derived this additional cost from spending projections that originated with DOE and by extending spending on activities contained in DOE's 2001 Budget request through the scheduled completion of the Project. Likely enhancements to the NIF Project would add another $180 million to the cost before it is completed. These additions bring the total cost to build and commission the NIF *on schedule in 2008* to $4.960 billion.

That cost estimate assumes there will be no more problems with the NIF Project, which could result in cost overruns or schedule delays. On the contrary, there is significant potential for future problems and delays. We have identified a number of technical problems that DOE has in meeting design requirements for the NIF, any one of which could require significantly more time to resolve than is currently scheduled.

Furthermore, construction costs are just the tip of the iceberg. To throw the switch and operate the facility would cost much more. DOE has dramatically underestimated the operating costs for the NIF. The Department's estimate of $145 million dollars per year is only a fraction of the likely operating costs. It excludes overhead costs and it excludes much of the cost of programmatic activities that DOE plans to carry out at the facility. When these and other appropriate costs are added to the DOE estimate, the projected cost to operate the NIF skyrockets to $440 million per year. A full accounting of the cost to build and operate the NIF for 30 years, as DOE plans, comes to $32.4 billion. This compares to only $12.2 billion using DOE current estimates and is six times what DOE claimed when the Project was first approved by Congress in 1995.

> We have documented a continuing pattern of increasing cost and declining performance expectations for the National Ignition Facility (NIF). In addition, we have highlighted several challenging technical problems, which DOE has not yet resolved. . . The NIF laser may never operate at its design energy or may do so for a very restricted number of experiments. Furthermore, the Project may not meet its most important scientific goal — ignition of fusion targets.

The Government is still paying interest on a sizable national debt. Thus, a complete picture of the Government's investment in an expensive facility, such as the NIF, should reflect interest imputed on the funds spent during construction. It is particularly useful to include interest when one compares cost estimates for alternate construction schedules in which the construction period differs significantly. Thus, a proper comparison between DOE's previous cost estimate for the NIF, which assumed completion in 2004, and current estimates of the cost to complete the Project in 2008 should include imputed interest. With interest imputed at the 10-year Treasury rate, DOE's previous cost estimate, made at the completion of the Title 1 Design in 1997, comes to $2.6 billion. That figure includes project-related costs, which DOE only acknowledged as part of its cost estimate in August 2000. In comparison, our estimate of the cost to build the NIF, including imputed interest, is $7.1 billion, if DOE can complete the Project in 2008. Each year of delay in completing the NIF would add $325 million in direct costs to the Project and an additional $400 million in imputed interest. A one-year delay would increase the cost of the Project, with imputed interest, to $7.8 billion. That is three times the comparable 1997 cost estimate and more than seven times the $1.1 billion cost estimate from the Conceptual Design, which DOE used to gain approval of the NIF from the Congress in 1995.

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After years of effort, DOE has theoretical designs for fusion targets that it believes could "ignite" and generate more energy than they absorb. Unfortunately, they are idealized designs with characteristics, such as near perfect smoothness. DOE has not been able to demonstrate that it can fabricate capsules, which meet the specifications of these designs.

Furthermore, DOE does not plan to demonstrate it can operate individual laser beams at full energy and focus them on targets before the project is completed. Even if individual beams can operate at full energy, it is likely that DOE will not be able to perform nearly as many full energy shots on the NIF per year as previously projected. That is because of the inability of key components in the laser to sufficiently withstand damage from the intense energy of the laser light (i.e. high light fluence). Based on our cost estimate, if DOE is unable to improve the damage resistance of the final optics and NIF is completed and operated anyway, it will deliver less than one-ninth the energy per dollar spent that was previously expected.

Recommendations

- **Because of the dramatic decrease in the expected return on the Government's investment in the NIF, continuing to fund the Project is no longer justified, if in fact it ever was. The NIF Project should be cancelled.**

- **Every taxpayer with an interest in cost-effective management of the U.S. nuclear weapons stockpile and Government efficiency should work to cancel the NIF Project as soon as possible.**

- **As preliminary steps, the Office of Management and Budget and the General Accounting Office should use this report as a reference in doing their own analyses of the full life-cycle cost of the NIF. In addition, Congress should commission a** *fully independent,* **technical and cost review of the NIF. These reviews should be the basis for congressional hearings examining the full cost of building, commissioning, and operating the NIF; examining whether DOE can meet its performance goals; and determining whether DOE is justified in continuing the Project.**

Endnotes

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9 It is customary to present cost estimates for DOE construction projects in "mixed dollars," which are escalated to the year in which they are expected to be spent. If not stated otherwise, we follow that practice here. That practice makes comparisons among cost estimates for project schedules that are completed in different years somewhat problematic. Inflation will appear to increase the cost of later projects, even if the constant dollar cost does not increase. While inflation may overstate the "constant dollar" cost of projects that are delayed, there are additional costs of delay that are not generally reflected in costs estimates adjusted solely for inflation. They include interest costs that may be attributed to a partially completed project while it is delayed and the opportunity cost of having to defer the use of a delayed project. As-spent cost estimates in mixed dollars are a compromise between constant dollar estimates and estimates that are fully-loaded with imputed interest and opportunity costs. This compromise is adequate for most uses.

It is important, however, to use constant dollars when comparing the decision costs of two or more options. We do that here, when we estimate the decision costs of completing and operating the NIF. That cost represents the real savings possible if NIF is cancelled this year. Our estimate of the discounted future cost of building and operating the NIF for 30 years (with a discount rate of 6 percent per year) is $9.9 billion.

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57 This is our estimate of the cost to DOE weapons programs, other than the ICF Program, of doing experiments on NIF from 2004 to 2008, while it is still under construction. We have included operating costs related to NIF from the ICF Program (such as operator training, conduct of operations, and target design and test activities) during those years in our estimate of the cost of building the NIF. We did not include programmatic operating costs in our estimate of the project-related costs to build and commission NIF. However, it is appropriate to include those operating costs here.

58 Discounting is the standard method of accounting for the time value of money. It recognizes that considerably less than $1 million is needed today to pay a $1 million dollar liability that will not come due for thirty years. As little as $174 thousand dollars invested in a 30-year bond, which pays six percent interest, would provide $1 million to pay a bill that comes due 30 years from now. In the case of the NIF, it is proper to discount the life cycle cost to the present, using an appropriate discount rate, to determine the true cost in today's dollars of continuing the project to its completion.

59 The beam availability schedule for the August 2000 baseline is from Appendix E of the Carlson-Lehman Review. Op. cit.

The beam availability schedule for the 1997 Title I design is from Kilkenny, J.D., et. al. *LLNL activities to Achieve Ignition by X-Ray Drive on the NIF.* July 20, 1998. UCRL-JC-131510 and from the Construction Project Data Sheet sent to the Congress in September 2000.

The number of shots per year is assumed to ramp up and reach the design level of 600 per year in the second year of operation of all 192 beams. If it is not limited by damage to the final optics, we assume that the shot rate would increase to 1200 shots per year over a three-year period beginning in the third year of operation of all 192 beams. This is consistent with the design requirement of 600 shots per year and DOE's stated intention to increase the shot rate to 1,200 shots per year.

The maximum energy per beam (9.4 kJ on target) is the total design energy of 1.8 MJ divided by 192 beams. For the current baseline, we assume operation at half power (maximum fluence of four J/cm2) until July 1, 2007 per the letter of May 30, 2000 from Bruce Tarter to Bill Richardson stating, "NIF. . . will begin to ramp up laser fluences only after mid-FY2007". We assume that some full power shots begin then, but their number is limited by the damage threshold of the final optics. For the full success in meeting final optics damage threshold option, we assume that the damage threshold is increased to the original design requirement over a two-year period.

The shot distribution (when not limited by damage to the final optics) is modeled as 25% of the shots at full power, 50% of the shots at half power, and 25% of the shots at lower power (low power shots are assumed to average 1 kJ/beam). This assumption is generally consisted with the information on the types of experiments and the energy per shot required for various users in the April 1997 *Facility Use Plan*, Op. cit.

The current damage limits for the final optics is taken from a chart titled, "NIF lifetime projection for 3ω optics can be based on tests of bare fused silica in vacuum" in the SEAB NIF Task Force meeting notes of 11/29/29. Per that chart, at 4 J/cm2 (one-half of full energy) the damage limit is reached at 320 shots and at 8 J/cm2 (full energy) the limit is reached after only 35 shots. Under the assumption that DOE would replace the final optics as often as three times per year, the number of shots per year at 4 and 8 J/cm2 was modeled by the following equation: $x/35 + y/320 = 3$; where x is the number of 8 J/cm2 shots and y is the number of 4 J/cm2 shots. This is an oversimplification of the damage dynamics, because it does not account for the order in which the shots occur, but should give a reasonable approximation of the number of shots allowed per year. This equation is used for the case with no improvement in final optics damage threshold. For that case, full energy shots are assumed to be initiated in July 2007 at a rate of 50 per year and ramp up to 80 per year over two years. Per the equation, with 80 full power shots per year, no more than 230 shots are allowed at half-energy (4 J/cm2) and the remaining shots (to the annual limit of 600) are lower power shots. Larger numbers of full power shots would significantly reduce the number of half power shots.

60 U.S. General Accounting Office. *Department of Energy: Opportunity to Improve Management of Major System Acquisitions.* Chapter Report. 11/26/96. GAO/RCED-97-17.

61 *National Ignition Facility Functional Requirements and Primary Criteria, Revision 1.6.* Op. cit.

62 *BCP No. 00-015.* Op. cit. p. 2.

63 In its report on NIF, GAO reported, “Senior officials from Lawrence Livermore, the University of California, and DOE concluded that the NIF managers were overconfident about their own abilities to solve project problems.” GAO NIF Report. Op. cit. p. 15.

64 See, *When Peer Review Fails: The Roots of the National Ignition Facility (NIF) Debacle.* Op. cit.

65 NAS NIF Report. Op. cit.

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67 Technology Resource Group of the NIF Council. *NIF Technology Review,* John L. Emmett, Chair. Nov. 4, 1999. (Also known at the Emmett Group Report.) p. 6.

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Glossary of Terms

Ablation (ablate) – The rapid absorption of energy on a surface and evaporation of some material from the surface. In inertial fusion, the rapid ablation of material from the surface of pellets containing fusion fuel may compress and heat the inner portion of the pellets sufficiently for fusion to occur.

Ablator – Material on the outer surface of ICF capsules, such as those planned for use on the NIF. DOE has examined several different materials, but has not be able to fabricate pellets, which meet the specifications for ignition in the NIF, from any of them.

Beamlet – A test laser operated at LLNL until 1999. Beamlet was to be a test bed for a single beam of the NIF laser, but LLNL never operated the Beamlet in accordance will all of the specifications of the NIF.

Bundle – Eight laser beams on the NIF.

Calorie – A unit of energy equal to the heat required to raise the temperature of one gram of water from 14.5 to 15.5 degrees Celsius. Also equal to 4.19 joules.

Conceptual Design – A preliminary design activity for a complex project. The basic design features, performance parameters, and layout of the facility and its major components are generally established at this phase. The design does not include details needed to actually build or assemble components.

Cryogenic Targets – Experimental targets used in ICF facilities, including the NIF, that contain hydrogen, deuterium, or tritium in solid form. For these isotopes of hydrogen to remain solid, the targets must be kept at temperatures below about 20 degrees Kelvin, or minus 253 degrees Celsius.

Defense Nuclear Agency (DNA) – see Defense Threat Reduction Agency.

Defense Special Weapons Agency – see Defense Threat Reduction Agency.

Defense Threat Reduction Agency – Agency of the DOD that among its tasks has the primary responsibility for studying the effects of nuclear weapons on military systems. This mission was previous assigned to the Defense Special Weapons Agency and before that to the Defense Nuclear Agency. All three agencies have participated in establishing the requirements for the NIF for weapons effects testing. The Defense Threat Reduction Agency would like to perform tests and experiments on the NIF.

Deuterium – An isotope of hydrogen whose nucleus contains one neutron and one proton and is therefore about twice as heavy as ordinary hydrogen, which contains only a single proton.

Diagnostics or diagnostic equipment – Equipment and instrumentation used to collect and analyze data from experiments. Eighty types of diagnostic equipment have been proposed for the NIF, including charged coupled device (CCD) cameras, high energy x-ray imagers, neutron imagers, various types of spectrometers, charged particle detectors, and fast framing cameras.

Direct-drive – Inertial fusion approach in which laser light is shone directly onto pellets of fusion fuel. The light from the lasers directly ablates the outer material of the pellets and compresses the inner portion of the pellets. Less energy may be needed to ignite fusion pellets with this approach than with indirect drive. However, to achieve the required symmetry, the beams must strike pellets from more different directions and each beam must be highly uniform across its face. (See also indirect-drive.)

Effects testing – See Weapons effects testing.

Final optics assembly – A pickup truck-sized unit for the NIF that is designed to be attached to the target chamber and hold several optical components, including KDP and DKDP crystals that comprise the frequency tripler, a final focusing lens, a debris shield to protect the other components from explosions in the target chamber, and a glass vacuum barrier. Components for four laser beams are to be mounted in a single assembly.

Flashlamps – Devices similar to the electronic flash units on cameras that turn electrical energy into short intense bursts of light. In a glass laser, such as the NIF, light from a large number of flashlamps is shone onto the neodymium glass laser slabs to provide the energy that powers the laser.

Fluence – The rate of energy flow past a particular point, expressed in units of energy per unit area, e.g. joules/centimeter^2. In the case of the NIF, the design requires that the final optics withstand fluences of laser light of 8 J/cm^2 averaged over the 40 cm square face of the optics components. Current optical components can withstand approximately 4 J/cm^2.

Fusion – The joining together of two light nuclei (such as deuterium and tritium) to form a heavier nucleus. Large amounts of energy are given off in this process, which powers the stars and hydrogen bombs.

Frequency doubler (tripler) – A component of the NIF that doubles (or triples) the frequency of the laser light passing through it. Frequency tripled light from the NIF is expected to be more effective at transferring its energy to targets than would be unconverted light.

General and Administrative costs – A component of the overhead charged to all programs at DOE laboratories and manufacturing facilities.

Hohlraum – With regard to the NIF, a Hohlraum is a hollow body that absorbs intense light energy and re-emits it as x-rays. The x-rays may be used for nuclear effects testing or other nuclear weapons experiments or may be used to compress a fuel pellet for experiments related to inertial fusion.

Hydrogen bomb – A nuclear weapon that derives must of its energy from fusion. (see thermonuclear weapon).

Inclusion – An impurity in a highly pure glass or crystal.

Inertial (confinement) fusion facility – An experimental facility that uses powerful lasers or particle beams to heat and compress small pellets of material to extremely high temperatures and pressures. Large inertial confinement fusion facilities, including the NIF, are designed to compress pellets containing deuterium and tritium and confine the material sufficiently long for fusion reactions to occur that will give off more energy than is absorbed.

Ignition – The process of starting a self sustaining reaction in a fuel mixture. With regard to the nuclear fusion reactions, which might occur in the National Ignition Facility (NIF), ignition would occur if the majority of the heat from early fusion reactions (which are themselves initiated by heating and compressing fuel with a laser), is absorbed in the fuel and helps induce additional fusion reactions.

Imputed interest – Interest that may be attributed to the cost of a construction project or other activity, but that is not actually paid in connection with the project or activity. One can impute interest costs to the NIF at the rate of U.S. Treasury Notes, because the Government could save such interest costs if the spending on the NIF were instead used to pay down the National debt.

Indirect-Drive – Inertial fusion approach in which laser light is shone into a hohlraum, which absorbs the light and re-emits it as x-rays that in turn shine onto pellets of fusion fuel, ablating the outer material and compressing the inner portions of the pellets. This is the initial approach planned for use in the NIF. (See also direct-drive.)

Inertial Fusion Energy (IFE) – The study and potential future use of inertial confinement fusion to produce useable energy in a cost-effective manner for commercial applications.

Infrared light – Light of somewhat longer wavelength (lower frequency) than visible light.

Isotope – One of two or more atoms with the same number of protons, but different numbers of neutrons. Atoms with the same number of protons have nearly identical chemical properties and are considered to be the same element. Different isotopes may have very differ properties in nuclear reactions.

Harmonic – An integral multiple of a basic frequency.

Joule – (abbreviated J) The basic unit of energy in the meter-kilogram-second (MKS) system of units. 4.19 joules equal one calorie.

Kilo – A prefix that multiplies a basic unit by one thousand.

Laboratory Directed Research and Development (LDRD) – Basic and applied research, outside of direct mission-oriented programs, which is funded at the discretion of the director's of DOE multiprogram laboratories. The source of the funds is a tax applied to all programs at the laboratories, which varies by lab from two to six percent. The LDRD rate at LLNL has been six percent in recent years and is not expected to change.

Laser – Derived from **l**ight **a**mplification by stimulated **e**mission of **r**adiation, it is a device capable of tremendous amplification and concentration of light energy into highly focused beams.

Laser and Target Area Building – The stadium-sized main building of the NIF, which houses the laser system and associated equipment, the target chamber, and the switchyard.

Lawrence Livermore National Laboratory – (Abbreviated LLNL) One of three Department of Energy Laboratories at which most of the research, development, design, and testing of U.S. nuclear weapons takes place. Located in Livermore, CA, which is about a one hour drive East of San Francisco, LLNL is the site of the National Ignition Facility (NIF).

Line-item – A specific item in the DOE budget that receives a separate appropriation each year. Each major construction project, such as the NIF, has its own line-item. However, only a portion of the total cost of the project is appropriated to the line-item. (See also Total Estimated Cost)

Line-Replaceable Unit (LRU) – The basic building blocks for the NIF laser. There are 42 different types of LRUs in the NIF design. Each is designed to be removed and replaced while affecting a minimum number of laser beams. The most lengthy task in the initial construction of the NIF is expected to be the insertion of about six thousand LRUs into the supporting infrastructure. The inside of the laser system must be kept extremely clean, while these insertions are done in the dirty environs of the Laser and Target Area Building.

Mega – A prefix that multiplies a basic unit by one million or 10^6. Often represented by the letter "M."

Micro – A prefix that divides a basic unit by one million or 10^6. Often represented by the Greek letter "µ."

Neodynium-doped glass laser – A laser whose primary light amplification occurs in glass in which a portion of the silicon atoms, which comprise the primary component of most glass, are replaced with the element neodynium.

Nuclear reaction – A reaction involving a change in an atomic nucleus, such as fission, fusion, or radioactive decay, as distinct from a chemical reaction, which is limited to changes in the electron structure surrounding the nucleus. A typical nuclear reaction releases one thousand or more times as much energy per particle (atom or nucleus) than a chemical reaction.

Nuclei – Plural of nucleus.

Omega Facility – A large ICF facility at the University of Rochester. Currently the world's most energetic laser, its 60 beams can deposit up to 40 kilojoules of energy on targets, which is one forty-fifth the design energy of the NIF.

Optics Assembly Building (OAB) – A separate building adjacent to the Laser and Target Area Building of the NIF where optical components will be delivered from offsite contractors, inspected, polished and finished, if necessary, and in most cases inserted into Line Replaceable Units. This building must be maintained under extremely high levels of cleanliness.

Other Project Costs (OPC) – In the DOE system of accounting for the costs of major projects, Other Project Costs are expenses funded from operating accounts that related to the project such as R & D necessary to complete construction, training and staffing, start-up planning, and costs for operational readiness reviews. There costs are included in the DOE calculation of Total Project Costs (TPC). DOE's definition of OPC does not include all costs related to the project. (see Other Related Operation and Maintenance Costs)

Other Related Operation and Maintenance Costs (OROMC) – A new cost category that DOE created in August 2000 to more fully represent the costs of the NIF Project. They are project-related costs funded from operating accounts that are not included in DOE's definition of Other Project Costs. DOE has determined that $1.2 billion in OROMC should be included in its cost estimate for the NIF. This report identifies an additional $1.332 billion in costs related to the NIF Project that are being funded from operating accounts, which DOE has still not included in its estimate of the OPC or OROMC.

Readiness in Technical Base and Facilities (RTBF) – One of three major categories in the DOE Budget. Funding is provided in RTBF for the physical and operational infrastructure, which DOE believes it needs to conduct the scientific, technical, and manufacturing activities of the Stockpile Stewardship program. Total funding for RTBF in 2001 is $1.6 billion, which comprises about thirty percent of the budget for Stockpile Stewardship.

Rebaseline – With regard to plans for a construction project, a rebaseline disregards a prior schedule and develops a new bottoms-up schedule and cost estimate.

Silica glass – A highly transparent glass composed of high purity silica (silicon dioxide), which is the primary component of normal glass. Also know as fused silica or vitreous silica.

Spectrometer – A highly specialized detector, which can simultaneously measure and display the intensity of electromagnetic energy (e.g. light) from a source as a function of the frequency (energy) or wavelength being emitted. Several spectrometers would be needed on the NIF to observe the energy emitted from targets over the complete frequency range from visible light to x-rays.

Stockpile Stewardship – The name for the program under which the U.S. Department of Energy manages nuclear weapons from cradle to grave. DOE spends about $5 billion per year on Stockpile Stewardship. The majority of the funds go to research and development to expand the understanding of nuclear weapons technology and to the design and testing of new concepts and components for nuclear weapons.

Switchyard – In the NIF facility, the large arrays of mirrors and supports, which direct the laser beams from the single orientation, in which they are created, to 48 separate directions from which they enter the target chamber.

Thermonuclear weapon – A nuclear weapon that derives most of its energy from the fusion of light nuclei into heavier nuclei under intense heat and pressure. The high temperature and pressure needed to initiate the thermonuclear reaction is produced by a preliminary (primary) explosion from a atomic bomb, which derives most of its energy from the fission of uranium and plutonium.

Third-harmonic – A frequency three times a basic underlying frequency. See harmonic.

Title 1 Design – Term used for the major design phase for Department of Energy construction projects. During the Title 1 Design, sufficient design details are determined and engineering drawings prepared to assure that all components and parts of the facility will fit together compatibly, deliver the proper outputs to each other, and be able to meet the specifications for the project. Large projects are typically broken down into thousands of small units, referred to as work packages, at this stage, and the cost of each work package is estimated in determining the total cost for the project. A master schedule is also prepared and used to resolve potential conflicts between activities and assure that related activities take place in the proper order. The detailed design of components and the preparation of engineering drawings from which components and buildings are constructed is completed during the Title 2 Design phase.

Total Estimated Cost (TEC) – A subset of the “Total Project Cost” in the DOE system of cost estimates for construction projects. A portion of the TEC is appropriated annually to a separate “line-item” for each construction project, which DOE is conducting. Those funds can be used only for that specific project.

Total Project Cost (TPC) – This is a DOE term of art that refers to a restricted set of costs, which DOE has determined should be charged to construction projects. Additional project-related costs are paid out of operating budgets and not normally attributed to construction projects, including the NIF.

Tritium – A radioactive isotope of hydrogen whose nucleus contains two neutrons and one proton and is therefore about three times as heavy as ordinary hydrogen, which contains only a single proton.

Ultraviolet light – Light of somewhat shorter wavelength (higher frequency) than visible light.

Weapons effects testing (simulation) – The process of exposing test equipment (generally military equipment) to the output (i.e. effects) of nuclear weapons (primarily x-rays and neutrons) in order to improve the design of such equipment to withstand nuclear weapons effects.

Yield – The total energy released in a nuclear explosion. It is usually expressed in equivalent tons (or pounds) of TNT (the quantity of TNT required to produce a corresponding amount of energy). One ton of TNT releases about one billion (10^9) calories of energy.

Z-Facility – A large ICF facility at the Sandia National Laboratory in Albuquerque, NM. It produces temperatures and pressures near those required for fusion by imploding cylindrical arrays of thin wires through which high currents are passed. The Z-facility is capable of depositing two MJ on targets, which is slightly higher than the NIF design energy of 1.8 MJ. The geometry of the Z-facility is, however, not as conducive to fusion at that energy as DOE predicts for the NIF.

Acronyms and Initialisms

CATS – Crystal Alignment Test System under development at LLNL for aligning the faces of KDP and DKDP crystals with their crystal axes.

CCD – Charged Coupled Device. The detector elements in highly accurate imaging devices or cameras.

CDR – Conceptual Design Report.

DKDP – (see KDP) - Crystals of potassium dihydrogen phosphate in which the hydrogen atoms have been replaced by deuterium. When certain frequencies of light is passed through consecutive crystals of KDP and DKDP that are properly aligned, a large percentage of the incoming light may be converted to light of three times the frequency.

DOD – U.S. Department of Defense.

DOE – U.S. Department of Energy.

DNA – Defense Nuclear Agency. (see Defense Threat Reduction Agency)

FACA – Federal Advisory Committee Act.

FY – Fiscal year.

ICF – Inertial Confinement Fusion.

IFE – Inertial Fusion Energy.

GAO – U.S. General Accounting Office.

G & A – General and Administrative costs.

KDP – Potassium dihydrogen phosphate. A crystalline material, which when oriented properly, is capable of converting a high percentage of light at certain frequencies when passing through it to twice its incoming frequency.

LANL – Los Alamos National Laboratory.

LDRD – Laboratory Directed Research and Development.

LLNL – Lawrence Livermore National Laboratory.

LRU – Line-Replaceable Unit.

LTAB – Laser and Target Area Building. The stadium-sized main building of the NIF, which houses the laser system and associated equipment, the target chamber, and the switchyard.

MJ – MegaJoules or millions of Joules.

NAS – National Academy of Sciences.

NIF – National Ignition Facility.

NNSA – National Nuclear Security Administration.

NTS – Nevada Test Site.

OAB – Optics Assembly Building.

OPC – Other Project Costs.

OROMC – Other Related Operation and Maintenance Costs.

PEIS – Programmatic Environmental Impact Statement.

R&D – Research and Development.

RTBF – Readiness in Technical Base and Facilities.

SEAB – Secretary of Energy's Advisory Board.

SNL – Sandia National Laboratory.

SSC – Superconducting Super Collider.

TEC – Total Estimated Cost. (see definition in the Glossary).

TPC – Total Project Cost. (see definition in the Glossary).

μ - The Greek letter "Mu". In scientific notation often used to represent the prefix "micro," which stands for one-millionth or 10^{-6}.

ω - The Greek letter "Omega". In scientific notation often used to represent frequency.