The National Ignition Facility is supposed to allow weapons makers to preserve the nuclear arsenal—and do nifty fusion science, too. But a new report that examines its troubled past also casts doubt on its future

Will Livermore Laser Ever Burn Brightly?

LIVERMORE, CALIFORNIA—The easiest way to start a fusion reaction is to detonate an atomic bomb. However, the United States swore off thermonuclear weapons testing in 1992, leaving scientists to find other ways to create and study fusion reactions. The National Ignition Facility (NIF), a superlaser being built at Lawrence Livermore National Laboratory in Livermore, California, is designed to overcome that problem by using lasers, rather than nuclear explosions, to create a fusion reaction. At an estimated cost of nearly $4 billion, it's the most expensive single project in the Department of Energy's (DOE's) research portfolio.

But NIF is over budget and way behind schedule. Originally, DOE officials estimated that the project, approved in 1993 and due to be finished in 2002, would cost about $2 billion. But not long after Secretary of Energy Bill Richardson announced at a June 1999 ribbon-cutting ceremony for NIF's target chamber that the project was "on cost and on schedule," officials were staggered by a string of revelations that stunned supporters and critics alike. First, NIF chief Michael Campbell resigned after admitting that he had never finished a claimed Ph.D. from Princeton University. Then an angry and "gravely disappointed" Richardson announced that Livermore officials had withheld news of serious technical and managerial problems (*Science*, 10 September 1999, p. 1647). The cover-up eventually cost several Livermore employees their jobs—and lab chief Bruce Tarter his annual raise. Finally, after months of review and a sweeping reorganization, DOE officials concluded in June that the laser's costs would jump to $3.26 billion, and that completion would be delayed until 2008.

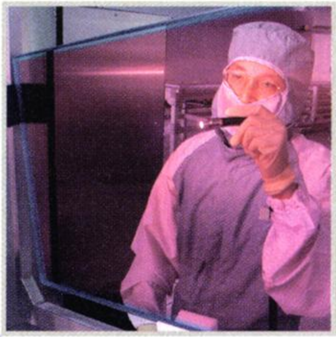
The turmoil is far from over. Next month, just as DOE delivers a long-awaited final update on the project's cost overruns, congressional critics are likely to try to kill or cut back the project, the latest in a long series of attacks. Even some of NIF's scientific and political allies are beginning to talk openly of a scaled-down version of the original 192-beam design. More than laser science is at stake: NIF's demise could drag down the Clinton Administration's $4.5-billion-a-year stockpile stewardship program, which was sold as a way to maintain the nation's nuclear arsenal without testing. Loss of the laser could also gut the Livermore lab, which depends on the project to pay salaries and attract new talent.

The critics have a new piece of ammunition: Last week, the General Accounting Office (GAO), Congress's investigative arm, completed a much-anticipated analysis of NIF's problems that finds plenty of things wrong. In a report to the House Science Committee, the GAO criticizes DOE and the University of California (which operates Livermore) for poor management and inadequate oversight. It also assigns the project a new, higher price tag of $3.89 billion. GAO chides lab officials for beginning construction of NIF's stadium-sized building before final plans for the laser were finished, producing a space that proved smaller than ideal. Beneath these administrative missteps, GAO says, lie engineering and physics challenges that are draining budgets. In addition to tighter fiscal reins, GAO recommends an "outside scientific and technical review of NIF's remaining technical challenges."

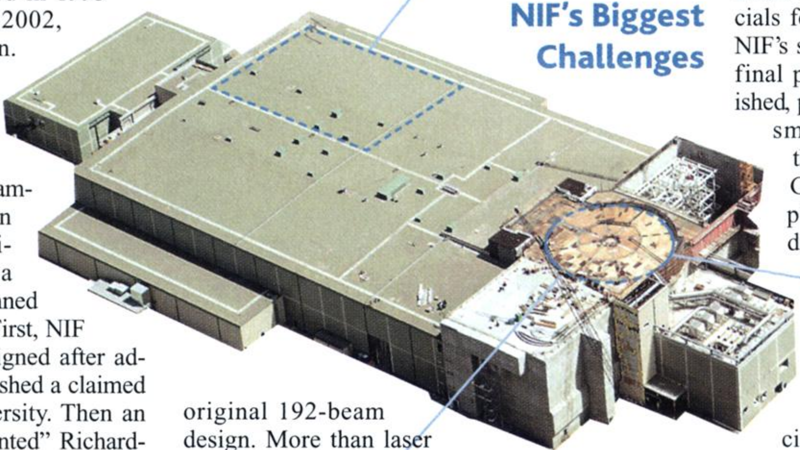
Although public officials are likely to talk mostly about money and management in the coming battle, NIF will ultimately stand or fall on whether scientists and engineers can overcome the daunting technical challenges. So far, NIF backers are confident. George Miller, an associate director at Livermore who oversees the project, says the lab can handle whatever problems arise. But he admits there are no guarantees. "In science, there is no sure thing," he says. "There are risks and uncertainties. We do our best to ensure that the risks are understood and acceptable."

Explosive science

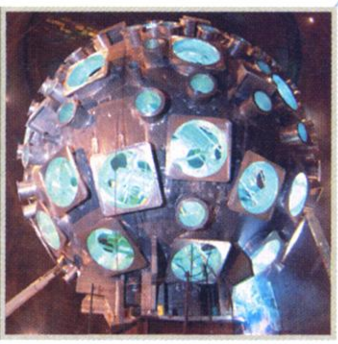
At its core, NIF is an expensive—and poor—substitute for an atomic bomb. After all, even a weak nuclear explosion can set



Laser Glass
The 150 tons of neodymium-doped glass at NIF's heart had to be made to precise standards. Contractors are finally learning how to manufacture the glass in bulk.



NIF's Biggest Challenges



Ultraviolet Optics
Before striking the target, infrared beams are converted to ultraviolet rays, wreaking havoc on optical components. A better understanding of materials may be needed.

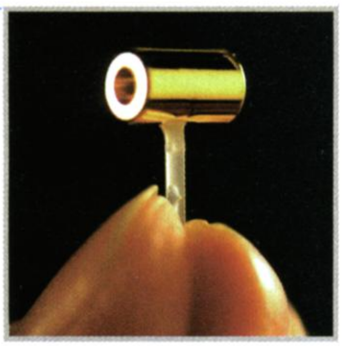
CREDITS: NIF

off a healthy fusion reaction. In contrast, when NIF is fired up and ready to go, the world's most powerful laser will focus its stupendous energy on a BB-sized pellet of heavy hydrogen that might or might not fuse (see page 1128).

That is because fusion reactions, unlike fission ones, are notoriously tough to start. Whereas fissile atoms, like uranium-235, break apart with the slightest nudge, deuterium and tritium need a huge kick to overcome their mutual repulsion and fuse, releasing energy. In the core of our sun, this kick is supplied by the collective gravitational attraction of hydrogen. On Earth, however, it's a much trickier thing to do.

Without the luxury of nuclear tests, scientists have been forced to look for another way to study fusion. The most promising method, and the one with the most direct applications to weapons research, uses lasers instead of bombs to start a reaction. This is what NIF is meant to do. When fully outfitted, NIF's stadium-sized laser will shoot 192 beams onto the inner surface of a small gold cylinder, called a hohlraum, that is smaller than the cap of a pen. The intense laser pulse will flash-fry the gold so that it radiates x-rays. Those x-rays, in turn, will smash into a hydrogen-filled pellet in the middle of the hohlraum, causing the outer layer of the pellet to evaporate. Just as a rocket is driven into the air by the explosion of hot gas out of a nozzle, the pellet will be crushed by the explosion of hot gas in all directions. Ideally, the hydrogen inside will be crushed so densely that it will ignite.

NIF packs nowhere near the energy of a nuclear weapon; the Hiroshima bomb, for example, was 30 million times more powerful than NIF's target energy. Still, NIF is incredibly potent by laser standards. Its 1.8 megajoules are nearly 60 times the energy of the previous laser record holders: NOVA at Livermore and OMEGA at the University of Rochester. Discharging all that energy in a few nanoseconds, the peak power will be 500 terawatts, more power than the entire world uses at any given moment.



The Target

The laws of physics conspire to keep the target capsule in the hohlraum (left) from imploding properly. NIF needs a smooth capsule, a symmetric implosion, and a lot of luck.

CREDITS: NIF

Although many take issue with the assertion, DOE claims that this brief flash of fusion energy will allow scientists to model the workings of the nuclear weapon's "secondary," the fusion part of a hydrogen bomb. In DOE's eyes, this makes it a cornerstone of stockpile stewardship (*Science*, 18 July 1997, p. 304).

Technical challenges

Building components that can handle NIF's power, from laser glass to the tiny targets, is the challenge at the heart of the project's technical problems. Even the hardiest materials degrade, explode, or eventually fail when subjected to such energy densities. Any one of the laser's more than 200 capacitors, for instance, "can vaporize and turn into a gas," as several did during tests at Sandia National Laboratory in New Mexico in 1998, says physicist David Smith of Sandia: "The shock wave breaks the insulation on the capacitor, which shoots out as shrapnel." As a result, engineers had to redesign the capacitor's shielding, putting each capacitor in a three-eighths-inch (0.95 cm) steel shell with flapper doors at the bottom. When one explodes, the doors pop open and the debris sprays toward the floor.

Producing laser glass in the necessary quantities and of sufficient quality is another ponderous task, and very costly. Early attempts to produce the 150 tons of neodymium-doped glass needed for NIF were marred by moisture- and platinum-based impurities. The problems forced Livermore and the manufacturers—Schott Glass Technologies in Pennsylvania and Hoya Corp. in California—to redesign their manufacturing methods, with some success. After much effort, Schott recently produced more than a ton of glass that is up to the proper specifications.

Even with glass that's up to snuff, the slightest speck of dust can burst into flame and destroy components. As a result, NIF components are assembled in clean rooms and are toted around by robotic trucks with superclean interiors. After initial difficulties with cleanliness, the problem appears to be under control, but only by straining an already overtaxed budget and further extending the construction schedule.

Other technical hurdles are equally daunting. The biggest is overcoming the so-called "three-omega" problem. (Omega is the symbol used by physicists to denote frequency.) The neodymium-doped glass produces light in the infrared region of the spectrum. According to John Lindl, a key NIF physicist, too much energy in the beam at long wavelengths produces a situation in which "you can't get light" to the target due to scattering effects. The energy is wasted and doesn't contribute to compressing the target. The problem is much smaller at higher frequencies, however, such as the ultraviolet region of the spectrum. Thus, NIF will use slices of enormous potassium- and phosphate-based crystals to triple the infrared beam's frequency (the three omegas) into the ultraviolet range. This solution, which predated NIF plans, required NIF scientists to invent another manufacturing process.

Keeping Clean

Even the slightest speck of dust can cause an explosion. The problem is now under control, thanks in part to robotic clean rooms.

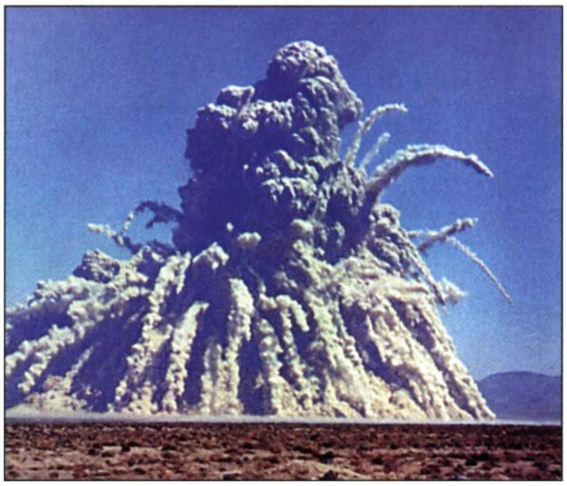
Unfortunately, ultraviolet beams are deadly to optical systems, especially at high power. As a result, these powerful beams of light cause small defects in the optics assemblies that handle the frequency-converted light, such as the lenses that focus the beam onto the target. These defects grow exponentially with each shot. At NIF's full power, the optics will have to be replaced every 50 to 100 shots or so.

"The three-omega optics were designed to be replaced," says Ed Moses, NIF's project manager. "The issue is how frequently you need to replace them." At a rate of once every 50 to 100 shots, operating NIF at full power—the requirement for ignition—would be extremely expensive. "This does not mean that NIF does not work or will not work," says Moses. "The question is how much will it cost to work?" He hints that an etching process might extend the optics' lifetime to about 1000 shots. But last year a NIF review committee suggested that the problem was so severe that it required a

Will NIF Live Up to Its Name?

The National Ignition Facility (NIF)—if it works as advertised—will pump almost 2 million joules of laser energy into a BB-sized pellet of hydrogen. Given all of NIF's problems (see main text), that feat would be a significant achievement in itself. But the bigger question is whether the result will justify the facility's name: Will the pellet actually achieve ignition—that is, undergo a sustained nuclear reaction that gives off as much energy as was put in? Most scientists on the project are cautiously optimistic. But others, some of whom are reluctant to speak publicly, have grave doubts.

"From my point of view, the chance that this reaches ignition is zero," says physicist Leo Mascheroni, a laser physicist formerly at Los Alamos National Laboratory in New Mexico and an outspoken critic of the project. "Not 1%. Those who say 5% are just being generous to be polite." Sandia National Laboratory physicist Rick Spielman sees it differently, however. "There is no unified position, and Leo is on one fringe." Not surprisingly, George Miller, NIF's associate director, stands at the other end. "When the last national-level study was done [in 1997], I think people put the odds [of achieving ignition] at better than 50-50. And in the intervening years, we have actually learned stuff that makes us more optimistic."



Bombs away. NIF hopes to achieve ignition without resorting to underground explosions such as this nuclear test from the 1960s Plowshare program.

Why the great uncertainty? One reason is that scientists have very little data on how hydrogen behaves at the temperatures and pressures that NIF will achieve. It's an environment less extreme than the interior of a nuclear weapon, but well beyond the conditions other lasers can create. Without testing data, scientists must use calculations and computer simulations to determine whether a capsule will ignite. "To keep the codes honest, you need to continually [gather data]," says Bedros Afeyan, a plasma physicist at Polymath Associates, an independent consulting firm in Livermore, California. "It needs some benchmark with reality."

One yardstick that does exist is clouded in controversy. In the 1970s and '80s, scientists at the Livermore and Los Alamos labs conducted a series of classified nuclear tests dubbed Halite-Centurion. Some of these tests involved sets of gold tubes, called hohlraums, with hydrogen pellets inside. After being bombarded with x-rays from nuclear explosions, the hohlraums reradiated x-rays that, in turn, crushed the hydrogen pellets. The hohlraums received varying amounts of energy—from tens to hundreds of megajoules, much greater than the NIF laser could ever dump on a target. But even with that much energy driving them, 80% of the capsules failed to ignite, says Mascheroni. Worse yet, he says, the failures couldn't be predicted with the computer codes that simulate nuclear explosions—and NIF dynamics.

Again, others dispute his claims. "I can't comment in detail," because the experiments are classified, explains John Lindl, a NIF physicist, "but we learned what we set out to learn." Miller says that Mascheroni's analysis is flawed because it's based on his work with hydrogen fluoride (HF) lasers, which operate on a much longer wavelength than the neodymium-doped glass lasers of NIF. "Sure, if NIF were an HF laser, it wouldn't get [ignition]," Miller says. The different frequency of HF lasers alters the laser's effectiveness; furthermore, Miller says that Mascheroni's calculations also ignore the "exquisite pulse shaping" that controls when the energy gets dumped into the capsule. "All these details matter," Miller adds. Mascheroni, in response, says he's taken these effects into account, and that pulse shaping won't have a dramatic effect on performance.

Another complication is that the amount of energy needed to achieve ignition has been a moving target. In the 1970s, Department of Energy (DOE) scientists predicted that their experiments would achieve ignition at 1 kilojoule. Over the years, according to Chris Paine, an analyst at the antinuclear National Resources Defense Council, that estimate grew steadily to 5 kilojoules (Livermore's Argus laser) and then to 200 kilojoules (the original design of the NOVA laser at Livermore) before reaching the current level of 1.8 megajoules. But in every case, an unexpected problem prevented ignition. "Given the state of knowledge in the late 1970s," Lindl confesses, "it looked like NOVA would be able to do ignition."

If all goes well, NIF is expected to reach ignition in 2010, about 2 years after it begins full operation and some 7 years after the target set by Livermore officials in 1995. Even such a belated success would be a surprise to some—and a huge relief to Livermore.

—CHARLES SEIFE

"significant materials science R&D program." The GAO also thinks that the three-omega problem poses "... a major technical challenge ... " and notes that "... there is currently no solution for this problem." Moses doesn't think the problem is a show-stopper, although he acknowledges its impact on the budget. "Again, it does not prevent NIF from working; it just doesn't meet spec with respect to the operational costs," he says. "[But] we have several years to work it through."

Even if the optics function properly and last long enough to keep the project within its budget, there are more fundamental physics problems that might derail NIF. Many involve the last stage of a laser shot—the moment when the pulse of light strikes the hohlraum and the resulting x-rays strike the supercooled target capsule full of hydrogen. At that instant, it's important that the x-rays compress the target in an entirely symmetric fashion. Even a tiny asymmetry in the implosion will cause the contents of the BB to squirt out in all directions, rather than to compress and ignite.

Tiny lumps on the target capsule's surface, uneven distribution of deuterium ice inside the target, and minute asymmetries in the incoming x-rays all create tiny ripples in the imploding plasma. As the capsule gets ever more compressed, those ripples get bigger and bigger. The result is a series of cold fingers invading the central core of hydrogen, causing the hot plasma to squirt in all directions. "We're basically trying to shrink a basketball-sized thing into a pea—it's a 30- to 40-fold convergence," explains Livermore's Lindl. "It's an inherently unstable process. [The plasma] doesn't want to be squeezed at these high densities and high velocities; it wants to break up into a bunch

CREDIT: DOE

of droplets."

Removing imperfections in the target eases the problem. "The outside of the [target] has to be smooth to within 50 nanometers on a millimeter-scale object," says physicist Steve Haan of Los Alamos National Laboratory in New Mexico. That's less than the height of a building-sized bump on Earth. The layer of deuterium and tritium ice on the inside has to be similarly smooth, to within about one micrometer.

Happily, the laws of physics offer some help. It turns out that a deuterium-tritium ice layer smoothes itself out. Because tritium is radioactive, it is constantly emitting electrons that warm up the surroundings; the more ice there is in a certain region, the hotter it gets. "It naturally produces a nice spherical shell," explains Haan. "It's really pretty cool, like a gift from nature."

But what nature gives, it can also take away. NIF's target capsule will be made of plastic or doped beryllium, but each type has its problems. Plastics, such as polystyrene, are relatively easy to manufacture to the required smoothness—and they allow scientists to see the layer of hydrogen ice inside so they can check the quality of the fill. Unfortunately, plastics aren't very good for the implosion itself, because they don't ablate, or vaporize, very well.

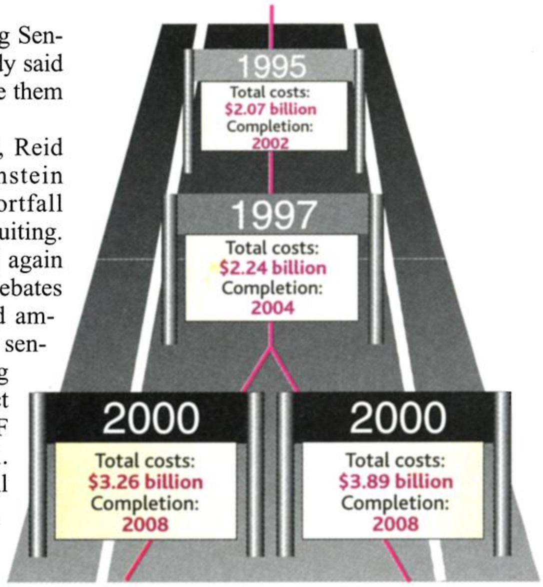
Beryllium is much better, especially when a small amount of a heavier metal such as copper is added. But the metal is opaque, so it's impossible to assess whether a beryllium target has been filled properly. Worse yet, it's difficult to make a perfectly round and hollow beryllium sphere.

"We could not, this instant, build a target that meets all of the NIF specs," concedes Livermore's Miller. "But we have demonstrated the technology that we're confident will allow us to make those targets when we need them."

Political realities

In the wake of NIF's problems, however, such assurances are less than totally convincing to the members of Congress who must approve NIF's funding. Spending panels in both houses have so far declined to give NIF the extra $150 million that DOE officials have requested to keep the project from falling ever farther behind schedule. Instead, they are waiting for the results next month of what DOE bills as an "exhaustive" review. And some lawmakers, including Senator Harry Reid (D–NV), have already said that NIF's poor track record has made them more stingy.

At a budget hearing last month, Reid tangled with Senator Diane Feinstein (D–CA), who argued that any shortfall would trigger layoffs and harm recruiting. That debate is likely to be repeated again next month, when the full Senate debates DOE's funding bill. With the added ammunition of the GAO report, several senators are rumored to be preparing amendments that would kill the project outright. But aides predict that NIF supporters will eventually prevail. "There is a great hesitation to imperil stockpile stewardship and Livermore, even though many members don't like what's happening with NIF," says one House aide.



Moving target. NIF scientists are running a race marked by rising cost estimates, receding completion dates—and now, diverging numbers from DOE (left) and GAO (right).

One potential hitch, however, involves how DOE proposes to pay for NIF's overruns. If NIF takes too much money away from other parts of the stockpile stewardship program, for instance, it could anger Defense Department officials and scientists at Livermore's sister labs—Sandia and Los Alamos—in New Mexico. That might lead Senator Pete Domenici (R–NM), a powerful player in lab budgeting, to take a dim view of NIF. So far, however, DOE has not publicly shared its funding plans, and Domenici has expressed only "concern" about NIF's future.

Concern about NIF may spread once the community digests the GAO report. Agency investigators, for instance, fault the lab for shunting aside fundamental scientific questions in favor of short-term engineering and construction fixes: "The laboratory [focused] too much attention on meeting construction goals at the expense of conducting and integrating necessary research and development solutions," the report concludes. Outside scientists agree. "Instead of pouring glass, they should be poring over data," says Bedros Afeyan, a plasma physicist at Polymath Associates, an independent consulting firm in Livermore.

Amid the uncertainty, Livermore chief Bruce Tarter is upbeat. "If we can get through the [DOE] review and get an initial OK by Congress to at least proceed," says Tarter, "… then I think I'm pretty—no, I'm *very*—confident that we're going to succeed."

But success may be hard to define. In 1995, Livermore envisioned carrying out six experiments a day at NIF; now they hope for two. And even achieving ignition is far from assured. "Half the value of NIF is in ignition," says Miller. "For me, if it doesn't get ignition, that will be a major disappointment."

Even without achieving ignition, however, NIF is expected to reveal properties of hydrogen at high temperatures and pressures that should be useful to astrophysicists as well as weapons designers. "NIF will provide good science," says Sandia physicist Rick Spielman. "It can do some really, really slick stuff." But without ignition, NIF won't be able to look at even higher pressure and temperature regimes that are critical to nuclear weapons designs. "It would have a significant impact" on the weapons program, says Spielman.

Miller agrees that if NIF fails to achieve ignition it could jeopardize political support for stockpile stewardship. "If we're not good enough to do NIF," he asks, "why should [Congress] believe us when it comes to stockpile stewardship?"

—CHARLES SEIFE AND DAVID MALAKOFF

Opposites attract. Protesters take issue with the continuing upbeat assessment of NIF by Livermore's Bruce Tarter *(left)*.

CREDITS: (LEFT TO RIGHT) NIF; J. KETSDEVER/*VALLEY TIMES* (PHOTO COURTESY TRI-VALLEY CARES)