On Target
Designing for Ignition

Guided by computer simulations and scientific collaborations, Department of Energy researchers at Livermore and Los Alamos are designing targets for the world's first laser ignition experiments.

F OR more than 40 years, laser fusion researchers worldwide have worked to achieve a momentous event called ignition, the fusion of atomic nuclei and the liberation of more energy than the fusion fuel first absorbed. The $1.2-billion National Ignition Facility (NIF), now under construction at Lawrence Livermore National Laboratory, promises to make that long-awaited event a reality.

NIF's 192 laser beams are designed to produce 1.8 megajoules of energy and 500 terawatts of power, more than enough to fuse the hydrogen isotopes of deuterium and tritium into helium nuclei (alpha particles) and yield considerably more energy in the process than was required to initiate the reaction.

By achieving ignition, NIF will allow weapons scientists to perform several kinds of experiments for the Department of Energy's Stockpile Stewardship Program to ensure that the U.S. nuclear arsenal remains safe and reliable. During ignition, NIF's targets will become miniature stars for about 10 trillionths of a second—a vanishingly short time, yet long enough to replicate aspects of physics at the energy densities and temperatures that occur during detonation of a nuclear device.

Of the 1.8 megajoules of energy produced by NIF, about 30 kilojoules is ultimately transferred into the deuterium–tritium fuel in the target. With ignition and successful burn, the fuel can produce some 600 to 1,000 times more energy than is put into it. That generous payback is not lost on energy scientists who will be using NIF to advance their understanding of how to deploy laser fusion as a cheap and safe civilian source of energy in the future.

The size of a covered sports stadium, NIF will house some three-quarters of an acre of high-precision optical instruments. And yet, the focus of its thousands of components will be a target of millimeter dimensions. The success of every NIF experiment will depend greatly on the ability to

design and manufacture the intricate, tiny targets so that their structure, materials, and manufacturing tolerances match the giant laser's power and energy and meet the goals of each particular experiment. The responsibility of designing the targets falls to researchers at Lawrence Livermore and Los Alamos national laboratories. The work requires coordinated effort from physicists, materials scientists, chemists, computer scientists, and technicians.

Physicist Steve Haan leads the Livermore effort to design ignition targets. For more than 20 years, experts such as Haan have conducted research on the design, production, and performance of target capsules as an integral part of Livermore's Laser Programs. Although the first shots on NIF will not occur before about 2002, with the first ignition experiments several years later, the team must finalize many aspects of the target design and fabrication technology well before that.

Codes and Computers Lend a Guiding Hand

In designing NIF targets, Livermore researchers are guided by increasingly detailed modeling that uses the latest generation of supercomputers. The modeling must account for a variety of physical phenomena that occur during an implosion and resulting ignition.

The simulations study the physics of both laser-driven hohlraums and capsule implosions. The study of hohlraums includes the refraction, reflection, and absorption of laser light passing through the hohlraum's laser entrance holes, the interaction of the laser light with low-density plasma, the conversion of absorbed laser light into x rays, the flow of those x rays within the hohlraum, and their absorption onto the ablator layer.

Capsule physics encompasses the variation of the capsule ablation, implosion, and hydrodynamic instability growth and mixing within the capsule, and the thermonuclear burn of the deuterium–tritium fuel.

The simulations reflect certain experimental realities: implosion is an inherently unstable process, and ignition experiments on NIF will involve neither perfectly smooth and spherical capsules nor a perfectly uniform field of x rays to ablate the outer layer and compress the fuel inside.

Several Livermore-developed codes are used because no single code can simultaneously model all ignition phenomena. LASNEX is a venerable two-dimensional radiation hydrodynamics code with very complete modeling of most relevant physical processes. Researchers use LASNEX to model the full geometry of the hohlraum and capsule as well as the incident laser beam. In these simulations, called integrated modeling, the capsule, hohlraum, and laser light are modeled simultaneously.

HYDRA is a three-dimensional radiation hydrodynamics code that contains all the physics necessary for imploding NIF ignition capsules. Additional features are being added that include hohlraum modeling and enable the code to run efficiently on massively parallel computers. In particular, HYDRA is used to study hydrodynamic instabilities in detail. Instead of simulating a hohlraum, the code models an x-ray flux to the exterior of the capsule.

Other codes model in detail the laser–plasma instabilities. A principal code for this application is F3D, which simulates the interactions of the laser light with the electrons and ions in the plasma.

Any one of these calculations can require days or even weeks of supercomputer time. As computers become faster, more and more detailed simulations can be done with acceptable turnaround time.

Researchers use Livermore's LASNEX code to model the target physics. The code is used to produce simulated data, such as this neutron image, which will be compared with data from NIF experiments.
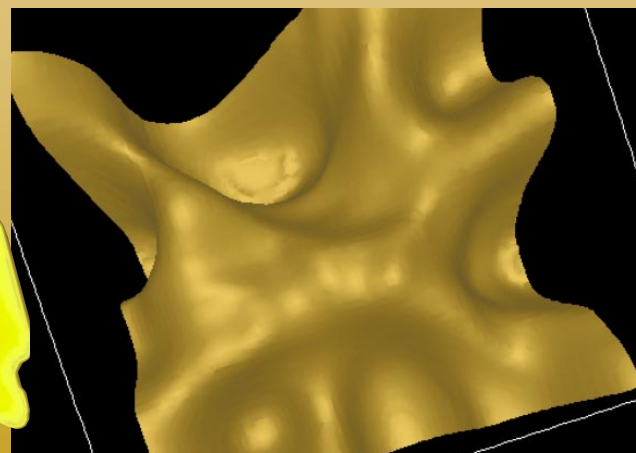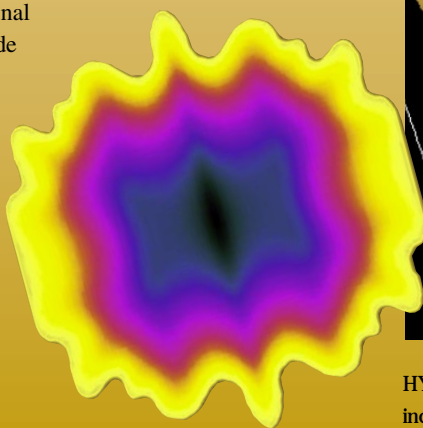
HYDRA 3D is a Livermore code used to model capsule implosions, including hydrodynamic instabilities, in detail.

Nova Provided Experience

The current Livermore effort builds upon a strong experimental program conducted on NIF's predecessor, the 10-beam Nova laser, which ceased operation in the spring of 1999. Many thousands of experiments on Nova led to an ever-increasing capability in target design and fabrication, diagnostic instrumentation, and computer simulation, as well as a firmer grasp of physics issues affecting ignition.

"Aside from giving us enormous experience with target design and fabrication," says Haan, "Nova showed us that NIF would be able to provide both the required hohlraum drive temperature and the laser symmetry to make ignition possible."

The team has also aggressively taken advantage of computer modeling. Livermore target designers use some of the most advanced computational facilities in the world to test target design options (see box on p. 5). The simulations give Livermore scientists good reason to believe ignition will be successful on NIF, says Haan. In fact, all indications are that NIF will provide a factor-of-2 performance margin above the ignition threshold.

The technical soundness of Livermore target designs has been validated by colleagues at other laser fusion research centers, both in the United States—at Los Alamos and the University of Rochester—and in Britain and France. In particular, French scientists from the research agency Commissariat a l'Energie Atomique, which plans to build a laser fusion facility similar to NIF, are collaborating with Livermore ignition target designers.

Ignition on NIF targets will involve compressing a 2-millimeter-diameter capsule that contains enough deuterium–tritium (D–T) fuel to achieve ignition and sustain burn. At first glance, the design resembles a typical Nova target, but it will be some four times bigger and will contain frozen D–T to help achieve conditions supporting ignition. The capsules will have a central volume of D–T gas, a frozen D–T solid-fuel layer, and an outer ablator layer.

For at least the first several years, ignition experiments will use indirect drive, in which laser light heats the inside of a gold cylinder called a hohlraum (Figure 1). The light is converted with close to 100 percent efficiency into an intense flux of x rays of almost 1,000 terawatts per square centimeter. The x rays will converge on the capsule's outer ablator layer, heating and expanding it. The
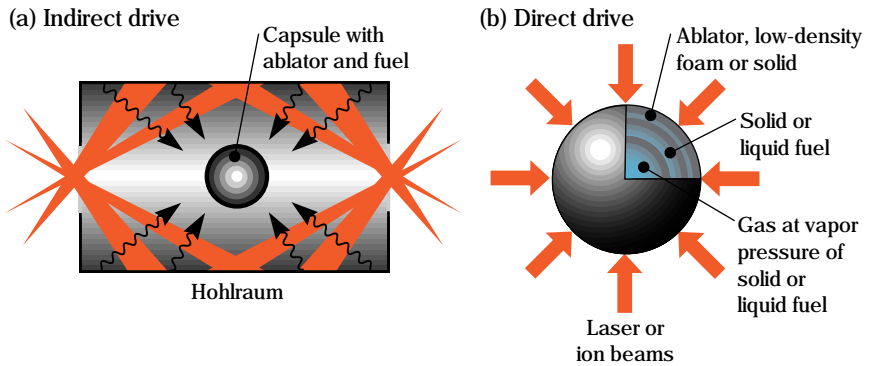

Figure 1. Ignition experiments on NIF will use indirect drive to heat the inside of a cylinder (hohlraum). The incident laser light will enter the cylinder through holes at its end caps and will be converted to x rays that will converge on a 2-millimeter-diameter capsule. NIF also has an option to conduct direct-drive experiments, with the laser light directly incident on a capsule.
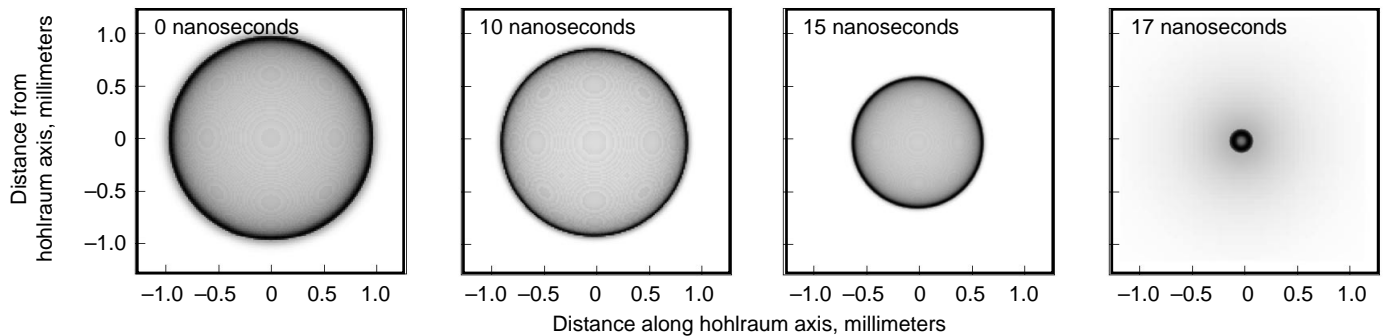

Figure 2. During implosion, x rays will converge on the NIF target capsule's outer ablator layer. The rocketlike blowoff of the ablator will then push the rest of the capsule inward, compressing the interior fuel to the extreme pressures and temperatures found in a star and a detonating nuclear warhead. The implosion can be backlit with x rays, producing data like the simulated images here, which show the implosion process from 0 to 17 nanoseconds. These images will be used to validate the timing and symmetry of the x rays driving the implosion.

rocketlike blowoff of the ablator will then push the rest of the capsule inward, compressing the interior fuel to the extreme pressures and temperatures found in a star and a detonating nuclear warhead (Figure 2).

Haan notes that NIF will also have the option of doing direct-drive ignition targets with the laser light directly incident on a capsule, thereby eliminating the need for a hohlraum. Experiments required to prove the feasibility of direct drive will be conducted over the next few years at the Omega laser of the University of Rochester's Laboratory for Laser Energetics (see *S&TR*, June 1999, pp. 19–21). Livermore researchers are participants in the Omega effort because direct drive on NIF has the potential to produce energy gains some three to eight times higher than indirect drive.

For the present, Livermore target designers are focusing on both the indirect-drive capsules and the hohlraums enclosing them. The baseline hohlraum measures about 10 millimeters long and 5.5 millimeters in diameter, with a 2.8-millimeter-diameter laser entrance hole on either end.

The hohlraum will be filled with an equal mixture of hydrogen and helium gas to minimize scattering of the laser light and to hold back the ionized gold. The gas will be contained within the hohlraum by 1-micrometer-thick polyimide foil windows that cover each hole. Before a shot, the hohlraum will be maintained at a carefully chosen temperature—around 18 kelvins (–255°C)—to keep the D–T fuel frozen and the central gas core at the right temperature and density (Figure 3).

Haan points out that while the baseline design has been fixed for some time, variations might prove to be important. The ability to shoot different targets, varying in design details to adjust for physics uncertainties, is a vital part of NIF's experimental plan. For example, different ablator materials and drive temperatures will give the team options to cover possible errors in current computer modeling.

Other target configurations will also be explored. For example, the target designers are researching the feasibility of a spherical hohlraum with four laser entrance holes in a tetrahedral configuration. The unique geometry might provide a more even x-ray illumination of the capsule (Figure 4).
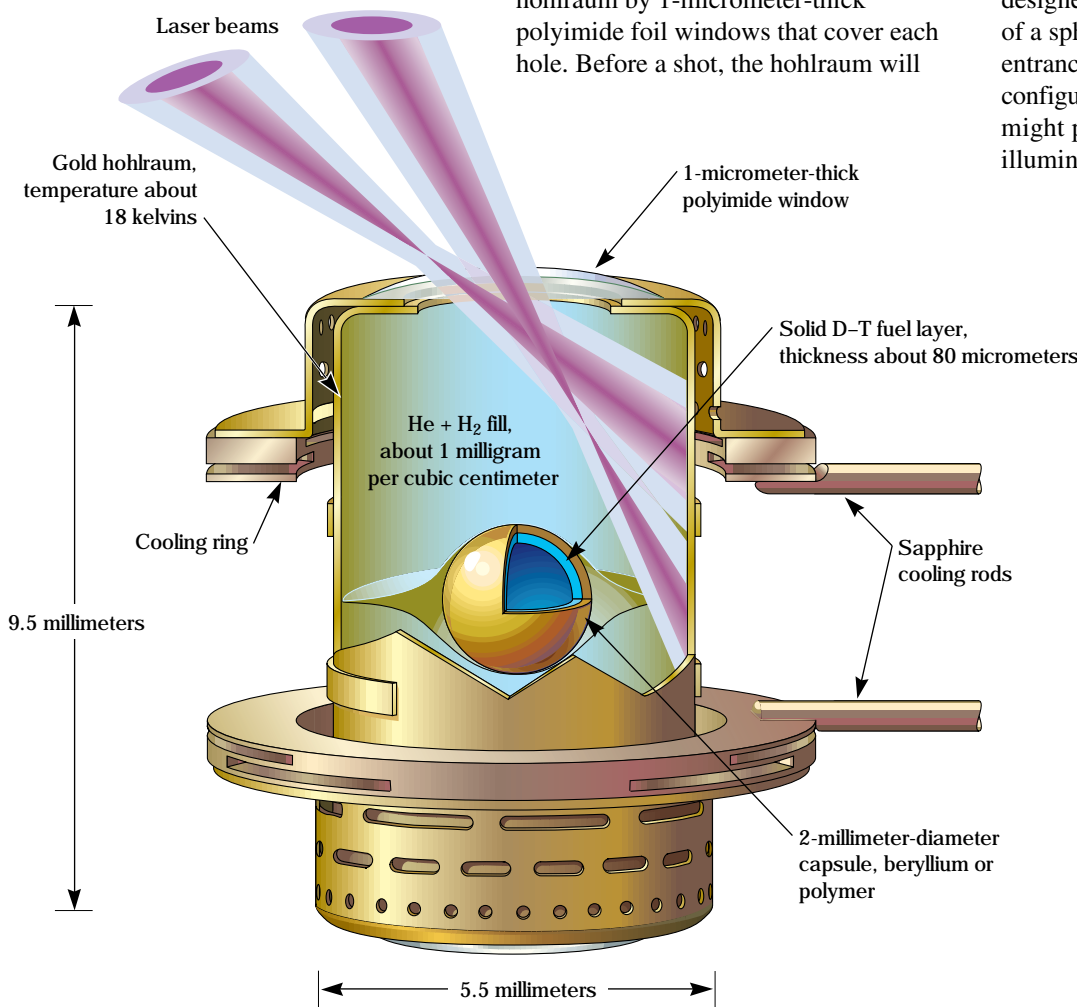

Figure 3. The hohlraum will be filled with hydrogen–helium gas (which will be contained inside polyimide windows) to minimize laser light scattering. The hohlraum will be maintained at 18 kelvins (see cooling ring) to keep the deuterium–tritium (D–T) fuel frozen and the central D–T gas core at the correct temperature and density.

Laser beams

Gold hohlraum, temperature about 18 kelvins

1-micrometer-thick polyimide window

He + H$_2$ fill, about 1 milligram per cubic centimeter

Solid D–T fuel layer, thickness about 80 micrometers

Cooling ring

9.5 millimeters

Sapphire cooling rods

2-millimeter-diameter capsule, beryllium or polymer

5.5 millimeters

Forming Cones of Light

Laser light of 0.35-micrometer wavelength will enter the laser entrance holes to form two cones: an inner cone that illuminates the hohlraum wall near the equator of the capsule and an outer cone that illuminates an area of the wall closer to each hole. In turn, each inner and outer cone will be composed of two subcones (Figure 5).

NIF's 192 beams are clustered in 48 groups of 4 beams so that there will be 8 spots in each of the two inner cones and 16 in each of the two outer cones. The large number of NIF beams will allow the laser illumination to more closely approximate a uniform x-ray field than did Nova.

Nevertheless, a basic asymmetry will still exist because of hot spots heated directly by the laser beams and cold spots where heat is lost through the laser holes. Because ignition is dependent upon smooth x-ray illumination of the capsule, target designers intend to reduce asymmetries in the x-ray flux to less than 1 percent by properly locating the laser-heated hot spots, adjusting the exact length of the hohlraum, and modifying the laser pulse intensities.

Haan says that two key factors influence the choice of the critical x-ray temperature that drives the capsule implosion. The first is laser–plasma instability. For the best target performance, the laser light needs to be absorbed in the gold hohlraum wall. Many forms of laser–plasma instability can occur as the laser light crosses the plasma before it is absorbed. These instabilities can cause laser light to be scattered back out of the holes or redirected so that it hits the wall someplace other than where it was originally pointed. In either case the result can significantly degrade the planned symmetry of the capsule implosion.

The second key factor affecting the choice of the x-ray temperature is Rayleigh–Taylor hydrodynamic instability (Figure 6). This instability magnifies small surface irregularities on the ice and ablator surfaces during the ablation phase of the implosion. Any perturbations can grow and eventually mix cold D–T fuel with the igniting hot D–T fuel. If the hot fuel is cooled too much by this mixing, it could fail to ignite.

The key to minimizing Rayleigh–Taylor instabilities is the x-ray flux onto the ablator surface. At higher fluxes, that is, at higher x-ray drive temperatures, the ablation of the material also carries off the growing perturbations. Initial perturbations are also minimized by making capsule layers as smooth as possible.

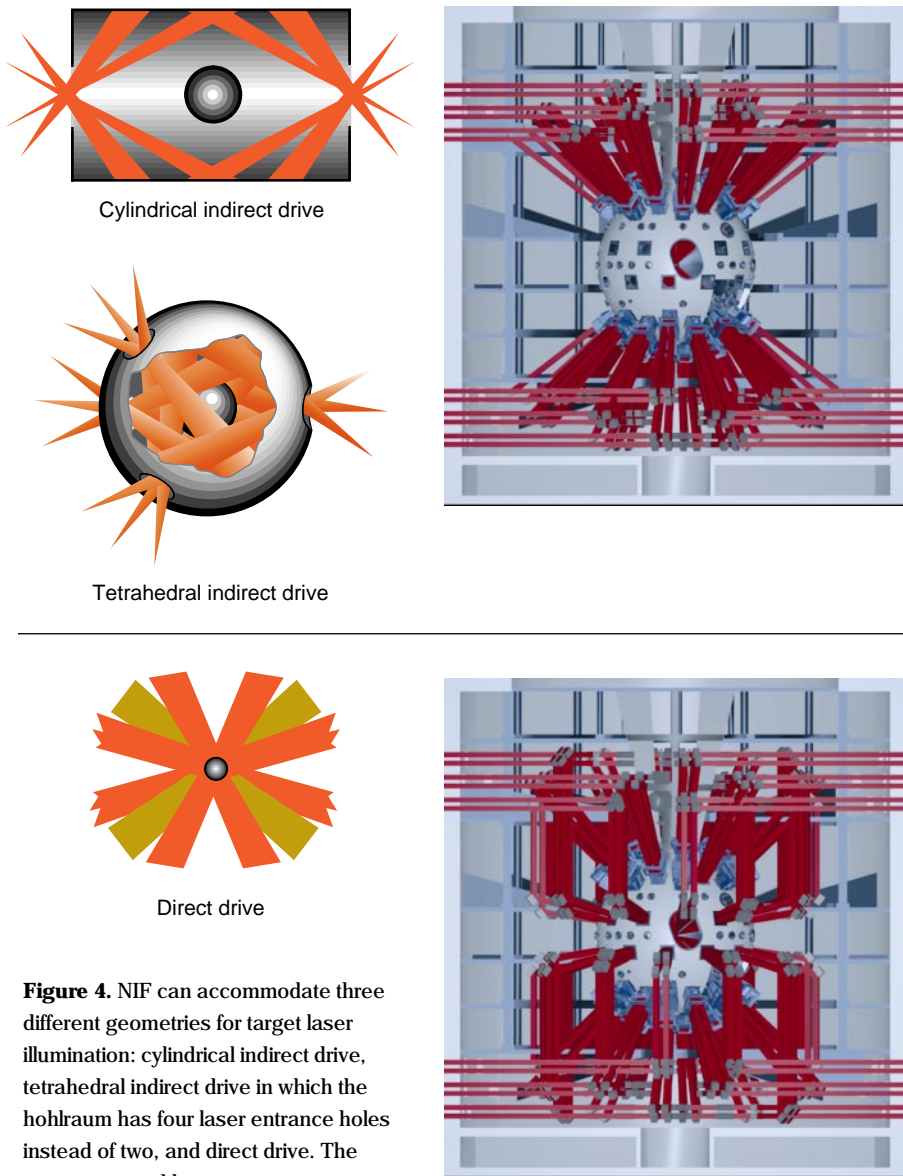Laser–plasma and hydrodynamic instabilities are complementary threats to ignition, and the targets are

Cylindrical indirect drive

Tetrahedral indirect drive

Direct drive

Figure 4. NIF can accommodate three different geometries for target laser illumination: cylindrical indirect drive, tetrahedral indirect drive in which the hohlraum has four laser entrance holes instead of two, and direct drive. The target area and beam-transport system relevant to cylindrical indirect drive and direct drive are shown at right.

intentionally designed so that the two threats are roughly balanced. Higher temperatures requiring higher laser intensities worsen laser–plasma instabilities but minimize hydrodynamic instabilities. In turn, low temperatures minimize laser–plasma instabilities but magnify hydrodynamic instabilities. As a result, designers have arrived at low and high x-ray temperature boundaries, about 250 electron volts and 350 electron volts, beyond which efficient implosion and ignition are difficult to attain.

For example, Haan and Livermore physicist Tom Dittrich designed and analyzed the simulated performance characteristics of a capsule to define a
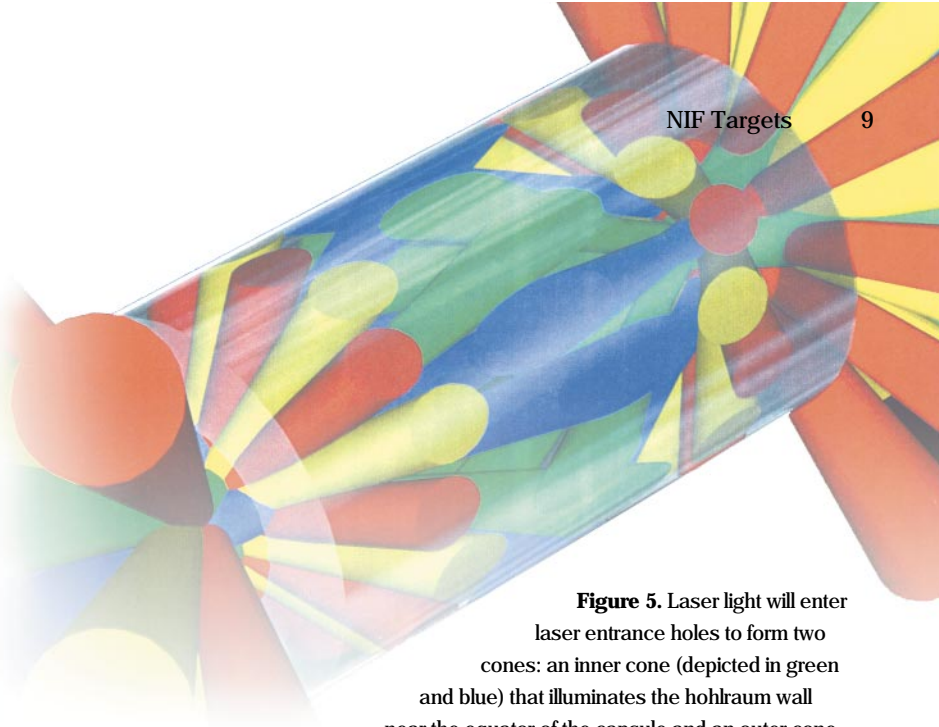
Figure 5. Laser light will enter laser entrance holes to form two cones: an inner cone (depicted in green and blue) that illuminates the hohlraum wall near the equator of the capsule and an outer cone (depicted in orange and yellow) that illuminates an area of the wall closer to each hole.

Target Builders Aim for Tighter Tolerances

NIF ignition capsules will be similar to those used on Nova, but four times larger and with considerably tighter tolerances for smoothness and roundness. Capsules built for ignition experiments must be close to uniformly spherical, or they will not ignite.

Livermore researchers have decades of experience fabricating plastic capsules for use on Nova and its predecessors. However, because of their exacting tolerances and dimensions, NIF ignition capsules will require either improvements to previous fabrication techniques or entirely new methods. Livermore manufacturing experts are working with colleagues at Los Alamos National Laboratory and General Atomics in San Diego, California, to explore ways to meet the rigorous specifications.

Livermore experts are planning to build plastic spherical shells from a liquid solution of polymers and then applying a coating of polyimide. For capsules with outer beryllium layers, Livermore researchers have explored sputtering the beryllium atoms onto the plastic shell. Los Alamos scientists have developed a technique that machines two beryllium-coated capsule hemispheres and bonds them with a submicrometer-thick joint of copper atoms. Upon heating, the copper diffuses into the beryllium, providing a uniform copper doping throughout the beryllium.

The capsules are filled with a precise amount of deuterium–tritium (D–T) at high pressure and temperature. The D–T gas diffuses through the shell until the desired fill is reached at a pressure of about 500 atmospheres. When it is cooled to the operating temperature of 18 kelvins (–255°C), the gas naturally forms an outer layer of solid D–T.

A central issue for capsule fabrication is surface roughness and defects in both the ablator surface and D–T ice layer. The D–T ice layer must be smooth enough so that it does not become too large a "seed" for hydrodynamic instabilities. Fortunately, in what Livermore target designer Steve Haan calls a "gift from nature," the D–T ice layer's natural radioactivity makes it smooth to within 1 micrometer, about what is required. Careful heating of the D–T with infrared light may allow even smoother ice surfaces. One advantage of beryllium ablator capsules is that they can tolerate a rougher D–T ice surface than polyimide capsules; a corresponding disadvantage is that the fuel cannot be smoothed beyond its natural roughness, because the beryllium is opaque to the infrared heating.

For either material, the ablator layer must be some 30 times smoother than the ice layer because it is more unstable during the implosion. Fortunately, the roughness of this surface can be controlled by the fabrication process or polishing.
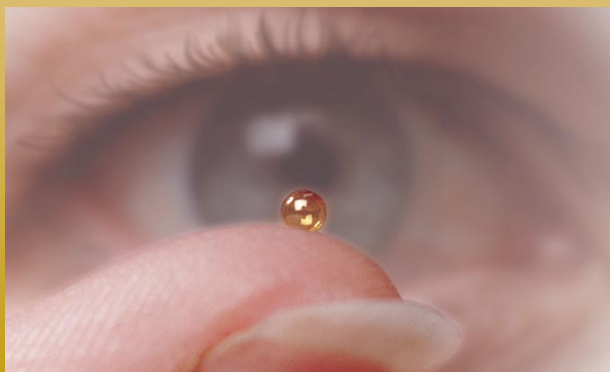
lower boundary on the successful implosion of an ignition capsule. The target requires only 900 kilojoules of laser energy and 250 terawatts of laser power from NIF, thereby lowering the hohlraum x-ray drive temperature from 300 electron volts to 250 electron volts. Because of the small size and low drive temperature characterizing this target, it is quite susceptible to Rayleigh–Taylor instabilities and would require very smooth surfaces. At the same time, laser–plasma instabilities would be expected to be minimal.

Ideal Is 300 Electron Volts

Haan says an x-ray-driven temperature of 300 electron volts seems to be an ideal temperature for capsule compression. Most of the model simulations used to set specifications have been done at this temperature. The baseline target uses 1.4 megajoules and 400 terawatts of laser energy and power, well within NIF's 1.8-megajoule and 500-terawatt specifications.

The choice of the x-ray temperature is crucial because it dictates the material forming the capsule's outer ablator layer, key to the implosion and subsequent ignition reactions. If this layer is smooth enough and bathed uniformly in x rays, its ablation will efficiently force the capsule inward at a velocity of about 400 kilometers per second (more than one-thousandth of the speed of light) and create the pressure and temperature required for fusion reactions to begin.

Livermore and Los Alamos target designers have tested a number of ablator materials (Figure 7). Polyimide is likely to be the best ablator at higher temperatures (up to 350 electron volts), while beryllium is the best at low temperatures (down to 250 electron volts). Polyimides are plastic polymers that exhibit an exceptional combination of thermal stability and mechanical toughness at a wide range of temperatures. They are often used as a protective coat for semiconductors.

Beryllium is attractive at lower hohlraum temperatures (250 electron volts) because it absorbs more energy and at lower temperatures produces higher pressure than plastic. The use of beryllium as an ablator has been explored since the earliest days of the laser fusion program. Its properties have so impressed Los Alamos target designers that they have adopted it as their standard ablator material and are working hard to devise ingenious methods to manufacture beryllium capsules (see box on p. 9).

One drawback to beryllium is that it is opaque to visible light, preventing optical inspection of the fuel. Beryllium ablator capsules also require a dopant with a high atomic number, typically copper, to better absorb the x rays. (Polyimide layers generally need no dopant because their opacity to x rays is about right.)

Both capsule designs must be cooled to 18 kelvins, colder than liquid nitrogen. That temperature is chosen to maintain in equilibrium the central, relatively low-density D–T gas and the high-density, 80- to 100-micrometer-thick D–T ice layer.

The D–T ice layer, the main fuel for ignition, lies just inside the ablator layer. As the capsule is compressed, this dense layer serves to contain the central volume, called the hot spot, at the temperature required for fusion to occur (around
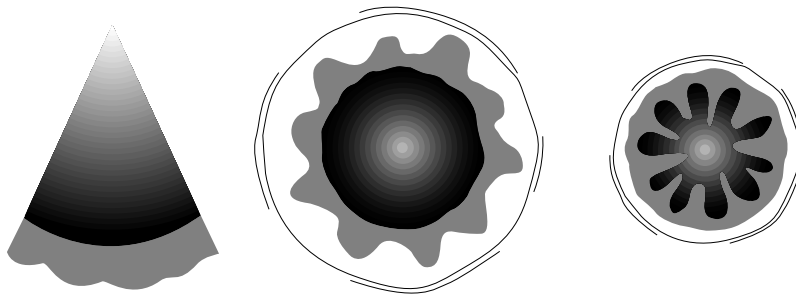

Figure 6. Rayleigh–Taylor hydrodynamic instability magnifies small surface irregularities on the capsule ice and ablator surfaces. If these irregularities grow large enough, they will prevent ignition.
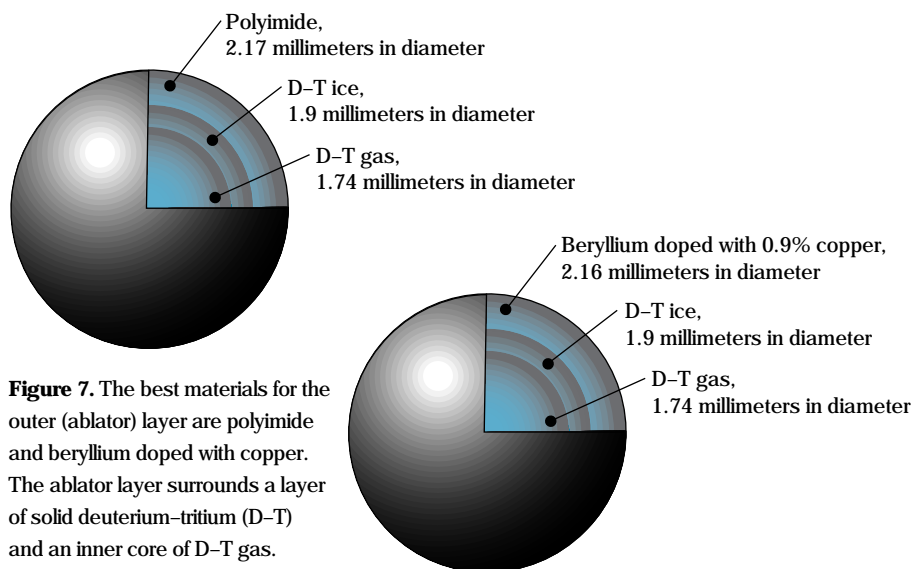

Polyimide, 2.17 millimeters in diameter

D–T ice, 1.9 millimeters in diameter

D–T gas, 1.74 millimeters in diameter

Beryllium doped with 0.9% copper, 2.16 millimeters in diameter

D–T ice, 1.9 millimeters in diameter

D–T gas, 1.74 millimeters in diameter

Figure 7. The best materials for the outer (ablator) layer are polyimide and beryllium doped with copper. The ablator layer surrounds a layer of solid deuterium–tritium (D–T) and an inner core of D–T gas.

10,000 electron volts, some 30 times hotter than the hohlraum). The burn from the hot spot eventually spreads into the surrounding dense D–T, which has been compressed during the implosion to a density of about 1,000 grams per cubic centimeter.

Performance Margin Tradeoffs

Haan says that NIF's performance margin should cover estimated uncertainties in the performance of the facility and the targets. Indeed, designers must be sufficiently conversant with the physics issues, targets, and specified tolerances of NIF optical components so they can systematically allocate various sources of asphericity. "Many factors contribute to making the capsule implosion not round," says Haan. "Most can be traded off against each other."

For example, capsules are manufactured to a certain degree of roundness, and laser beams will exhibit some deviations from their specified power rating. "All we care about is obtaining good spherical implosion," Haan says, "so we can tolerate poorer power balance if we manufacture more spherical capsules, or vice versa."

Haan emphasizes that ignition experiments will be preceded by a two- to three-year phase of experiments testing components, diagnostics, and various aspects of the hohlraum and target designs. The team plans to start out slowly, with noncryogenic and nonignition targets that are more forgiving of asymmetrical laser light. The team will not wait for all 192 beams to be up and running. Instead, target experiments will use four-beam clusters as soon as they are available.

"We want to proceed smoothly up the learning curve as we gain experience with the facility," says Haan. "The first couple of years will tell us exactly what we need to know to maintain the hohlraum at the desired temperature and achieve ignition."

With the aid of collaborations worldwide and rigorous computer simulations, the team—and the scientific community—is confident that NIF target designs will support ignition. Successful ignition will fulfill a dream of decades and usher in an era of experiments conducted at the extreme physical conditions found only in stars and detonating nuclear devices.

—*Arnie Heller*

Key Words: ablator, Commissariat a l'Energie Atomique, deuterium–tritium (D–T), F3D, hohlraum, HYDRA, Rayleigh–Taylor hydrodynamic instability, ignition, implosion, laser–plasma instability, LASNEX, Los Alamos National Laboratory, National Ignition Facility (NIF), polyimide, stockpile stewardship.

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About the Scientist
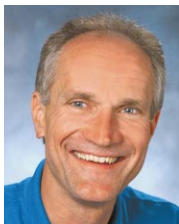
STEVE HAAN received a B.S. in physics from Calvin College in Grand Rapids, Michigan, and a Ph.D. in physics from the University of Maryland. He joined Lawrence Livermore in 1981, where he has concentrated on target design and modeling of inertial confinement fusion (ICF). He participated in the Halite–Centurion program of underground tests for ICF and currently is working on the theory and modeling of hydrodynamic instabilities in ICF targets, on the design and modeling of Nova and Omega experiments, and on the design and modeling of targets for the National Ignition Facility. In 1994, he was designated a fellow of the American Physical Society (APS). Along with coworkers, he was awarded the 1995 APS Award for Excellence in Plasma Physics Research. He is a 1999 recipient of the Edward Teller Medal in Inertial Fusion.