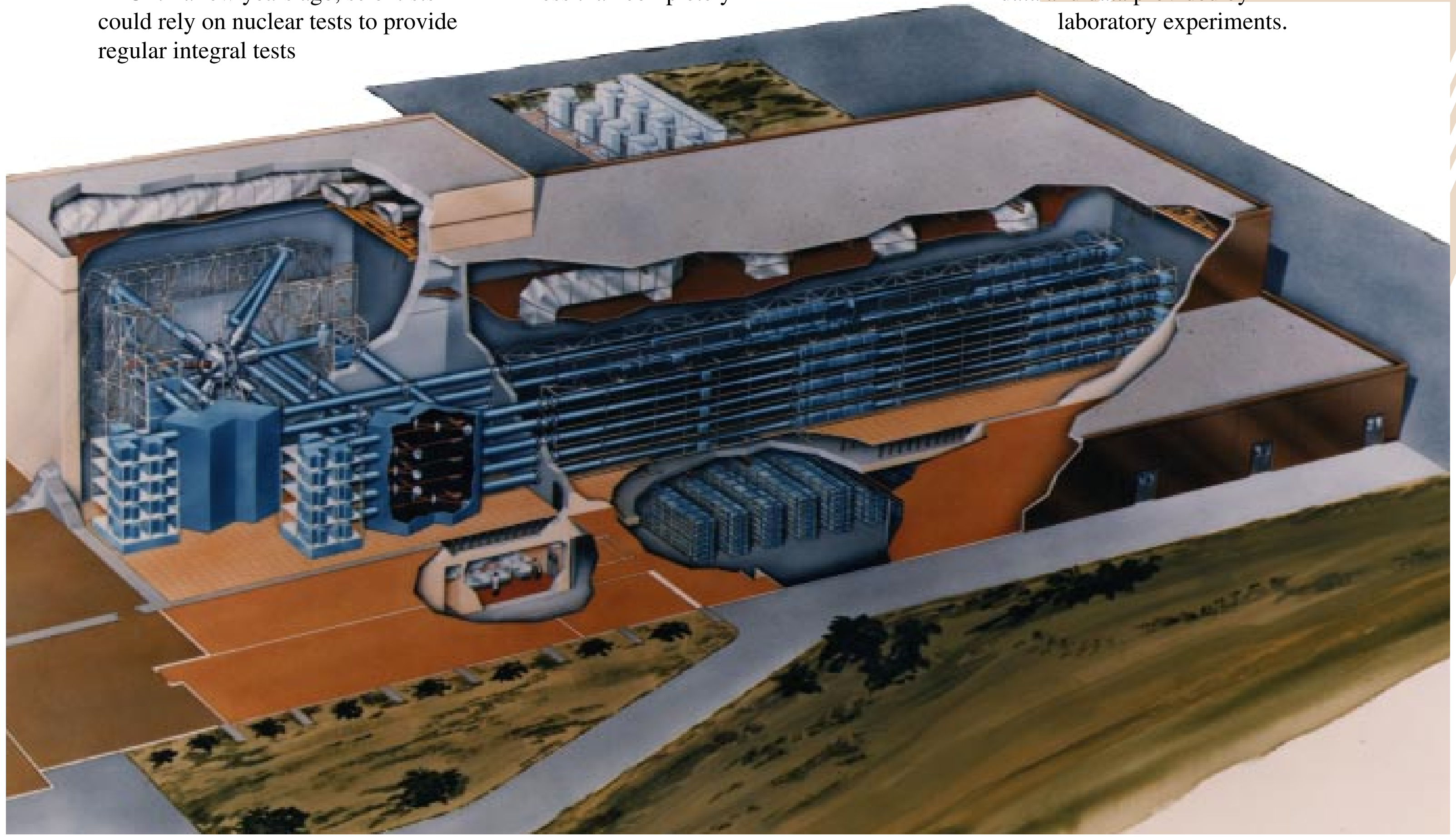
Nova Laser Experiments and Stockpile Stewardship

Livermore's Nova laser is proving to be a powerful laboratory tool in support of DOE's Stockpile Stewardship and Management Program.

THERMONUCLEAR weapons are extremely complex devices, both in design and operation. When a nuclear weapon detonates, it initiates a chain of physical processes ranging from chemical explosion to thermonuclear burning, not all of which scientists understand in every detail. Although sophisticated computer programs model these processes, such models unavoidably require many approximations.

Until a few years ago, scientists could rely on nuclear tests to provide regular integral tests of a weapon's performance. Only by actually testing weapons did they obtain the experimental data against which to measure their physical models and computer codes. This approach worked extremely well, as long as scientists did not stray too far beyond the body of direct evidence. The match between data and calculation steadily improved, leading to increasingly good prediction of overall weapon performance, even though some phenomena remained less than completely understood. Under these circumstances, the laboratories could, with great confidence, certify the safety and reliability of the nuclear stockpile.

Circumstances have now changed. The unavailability of nuclear testing requires new approaches to assuring the safety and reliability of our nation's nuclear stockpile. Notably, there is greater reliance on computer codes, the accuracy of which must be evaluated against historical underground testing data and data provided by laboratory experiments.



In a variety of experimental facilities, scientists are addressing different aspects of nuclear explosions. In the laboratory, the highest energy-density conditions (that is, the highest levels of energy per unit volume) are obtained mainly through laser research on inertial confinement nuclear fusion. Over the years, Lawrence Livermore has designed a series of increasingly powerful lasers, culminating in the National Ignition Facility, now under construction.[1] NIF will be a neodymium–glass laser system with 192 beams. It will be capable of delivering as much as 3 to 4 million joules of laser energy in millimeter-scale or greater volumes in less than 10 billionths of a second in a variety of wavelengths, pulse lengths, and pulse shapes. At peak power, NIF will generate up to 750 trillion watts of laser light.

Although far less powerful than NIF, Lawrence Livermore's Nova laser is a very potent machine with over a decade's operation to demonstrate its enormous value.[2] It is a neodymium–glass laser with ten beams. Typically operating at a wavelength of 0.35 micrometers and 40,000 joules in 2.5-nanosecond pulses, Nova produces 16 trillion watts of laser light.

Nuclear detonations produce very high energy-density. High-power lasers like Nova can approach such high energy-densities, even if only momentarily in very small spaces. Extremely powerful lasers can, in short, create microscopic versions of some important aspects of nuclear detonations, something available through no other experimental technique.

Using Nova, scientists have been able to explore at least the lower reaches of the high-energy-density regime in which the physics of nuclear weapons poses the most unsolved problems.[3] Figure 1 depicts the Nova laser facility in a cutaway view. Major optical components of a single Nova beamline are shown schematically in Figure 2.

Nova can produce the high energy-densities demanded by weapon physics experiments in two ways. Conceptually, the simplest is the method known as direct drive. All the laser beams focus directly onto the target, or physics package, in the target chamber. The absorbed energy delivers a strong shock to the target, compressing and heating it.

Although direct drive produces high energy-densities, this method has definite drawbacks. Simulating direct-drive experiments requires calculating the complex interaction of laser light with matter, an interaction not typically modeled in computer codes used for weapon design. Perhaps more significant are the high standards of laser uniformity and target fabrication required; even minor flaws of homogeneity or surface roughness may negate a direct-drive experiment. To avoid these problems, scientists have usually preferred to rely on an alternative method.

Instead of directly striking the target, the laser beams enter the open ends of a hohlraum, a hollow gold cylinder a few millimeters long (Figure 3). When the laser light strikes the inner walls of the hohlraum, they absorb the laser energy, which is transformed into an intense flux of x rays that heats the hohlraum and any sample it contains. Because the laser-generated x rays (rather than the laser energy itself) drive the experiment, this alternative mode of operation is known as indirect drive.

One advantage of the indirect-drive technique derives from the measurability and uniformity of the x-ray flux. The interaction of the uniform x-ray flux with matter also can be accurately modeled. Another advantage of indirect drive is the relative uniformity with which soft x rays heat a physics sample

Figure 1. Cutaway view of Nova laser facility when it opened in 1985. The space frame (right) supports the ten-laser amplifier chains. A system of high-reflectivity mirrors ensures that the ten laser beams arrive simultaneously at the target, centered in the spherical chamber (left).

in a hohlraum. Figure 3 shows two views of a typical Nova hohlraum; Figure 4 is a rendering of the target chamber housing the tiny hohlraum.

Although significant progress has also been made for direct-drive experiments, Nova is not configured to exploit this concept. NIF is designed to handle both indirect- and direct-drive experiments.

Essentially, physics experiments on Nova address two basic phenomena: hydrodynamics and radiation. Hydrodynamics is the physics of the motion of fluid materials. Strongly influencing hydrodynamic phenomena is a property of matter termed equation of state—the relationship between a material's pressure, temperature, and volume.

Radiation studies center on the emission, transmission, and absorption of energy in hot dense plasmas. Experiments determine the x-ray opacity of various materials and how it varies with temperature and density. They also address radiative heat transfer as well as the interaction of radiation fields with matter, including the absorption and re-emission of radiation.

Shocking Matter

The basic science of nuclear detonations begins with learning how matter behaves at high energy-densities. To describe these conditions in a particular material, scientists rely on an equation of state, which mathematically expresses the thermodynamic relationship between the energy content of a mass of material, its volume, and its temperature. High-energy-density equations of state are fundamental in describing such phenomena as hydrodynamics and radiation transport; their fundamental importance also makes them crucial in understanding the operation of nuclear weapons.

Suddenly adding large amounts of energy to a material system creates intense sound or pressure waves, which become shock waves. Shock compression is a widely used method for experimentally determining equations of state at high pressures. An experiment begins with determining the initial pressure, volume, and energy of the material. Compressed by a single shock wave to greater pressure, the material's volume changes to a new state at higher density, temperature, and pressure.

By varying the shock strength in a series of experiments from the same starting conditions, scientists can obtain a set of pressure–volume pairs. They can then plot these pairs to produce the material's Hugoniot—that is, the mathematical curve relating the velocity of a single shock wave to the pressure, density, and total heat of the transmitting material before and after the shock wave passes. Because of its relative simplicity, the Hugoniot is the primary avenue for investigating a material's equation of state experimentally.

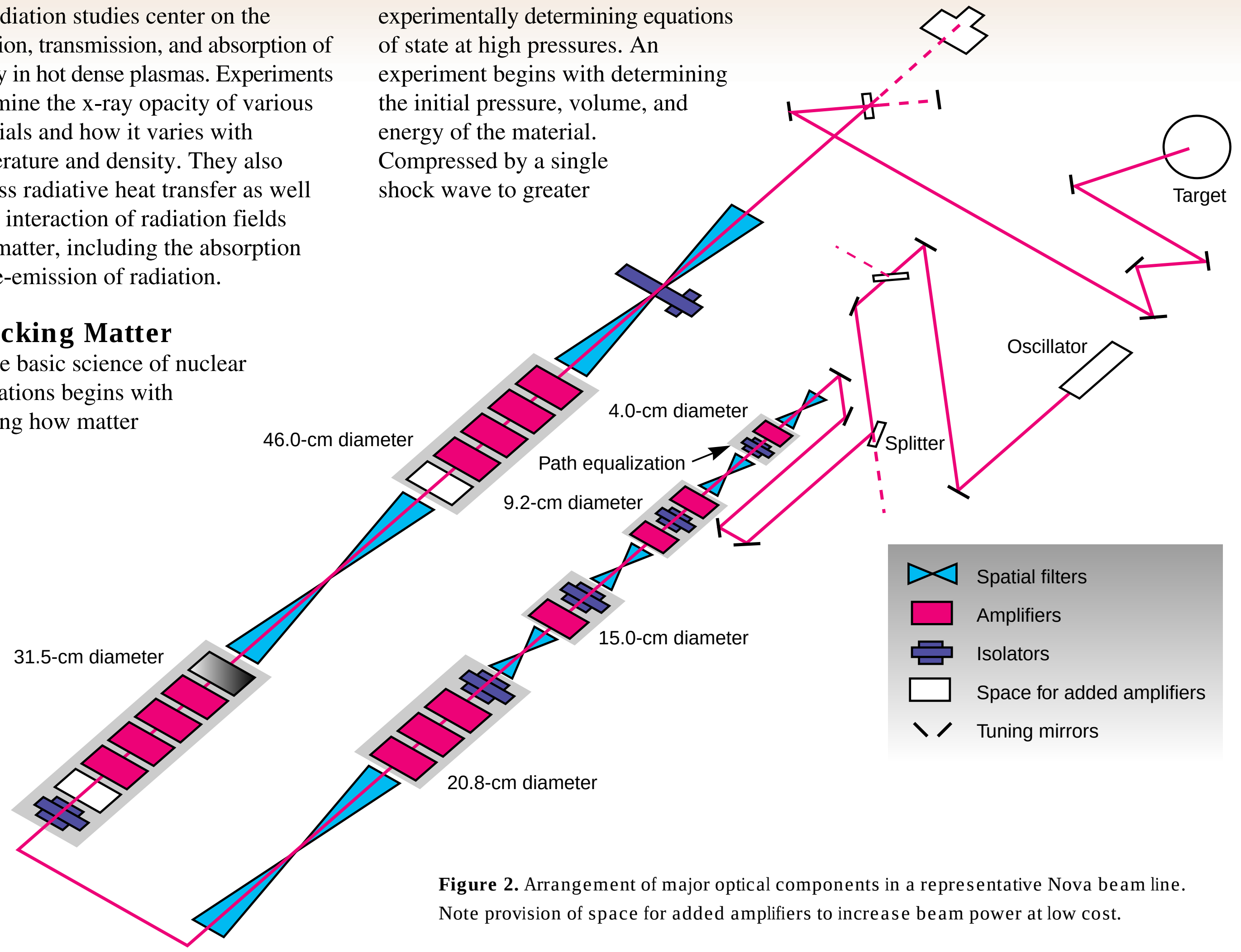


Figure 2. Arrangement of major optical components in a representative Nova beam line. Note provision of space for added amplifiers to increase beam power at low cost.

Each material possesses its own unique equation of state. No single valid model exists for the entire range of variables, which may cover many orders of magnitude in nuclear weapons operations. Thus, the equation of state for a particular material derives from models of limited scope for particular regimes of pressure, density, and temperature. These models are usually collected in a table of equation-of-state values that can be used in code calculations.

For nuclear detonations, the equation of state extends through two distinct regimes. In the early phase of implosion, before any significant nuclear yield, temperatures are relatively low and such factors as strength of material and chemical reaction are most significant. Scientists study this relatively low-energy-density regime through experiments using high explosives or gas guns (essentially converted cannons), which in high-density materials can generate pressures up to a few megabars—that is, up to a few million times normal atmospheric pressure. Such data determine the lower end of the curve in Figure 5, which shows the Hugoniot of aluminum.

Vastly higher pressures, hundreds of megabars, characterize high-energy-density regimes, where scientists formerly acquired data only through nuclear tests. Data points at the upper end of the curve in Figure 5 come, with large uncertainties, from openly published work based on the Soviet underground nuclear test program. Because of insufficient experimental data, scientists must interpolate the intermediate portion of the curve and extrapolate to pressures beyond the data.

At multi-megabar pressures, neighboring atoms are packed so tightly as to disrupt each other's outermost electron shells. The resulting ionization caused by pressure absorbs large amounts of energy and makes the material more compressible. Various theories predict different curves, as Figure 6 illustrates

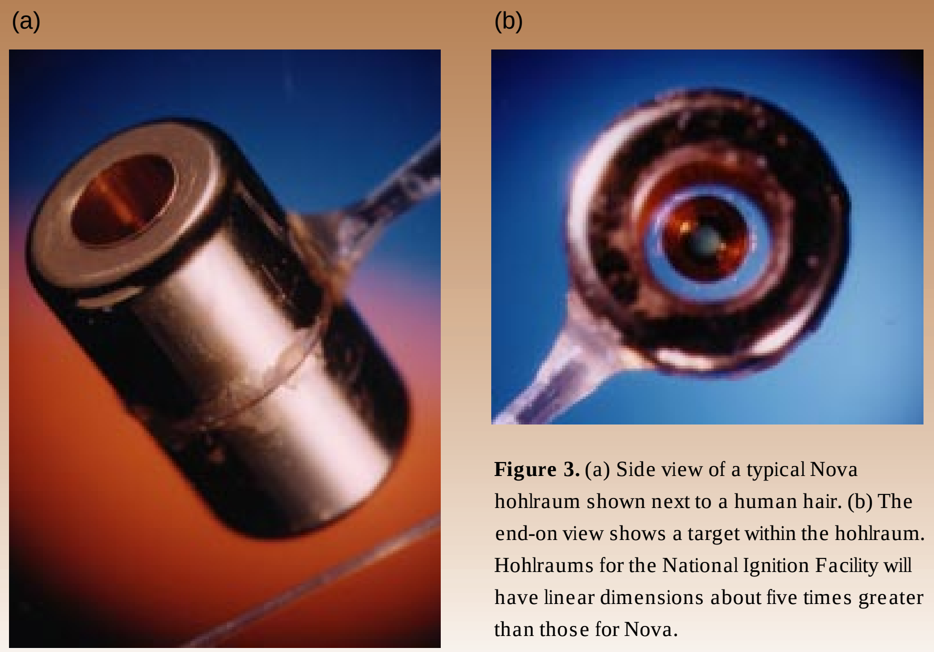


Figure 3. (a) Side view of a typical Nova hohlraum shown next to a human hair. (b) The end-on view shows a target within the hohlraum. Hohlraums for the National Ignition Facility will have linear dimensions about five times greater than those for Nova.

Figure 4. Artist's rendering of the outside of the Nova target chamber, where the ten laser beams converge to heat and shock a tiny hohlraum. Note the two human figures at work on the platform. The entire structure is three stories high, and the spherical target chamber is 4.5 meters (15 feet) in diameter.

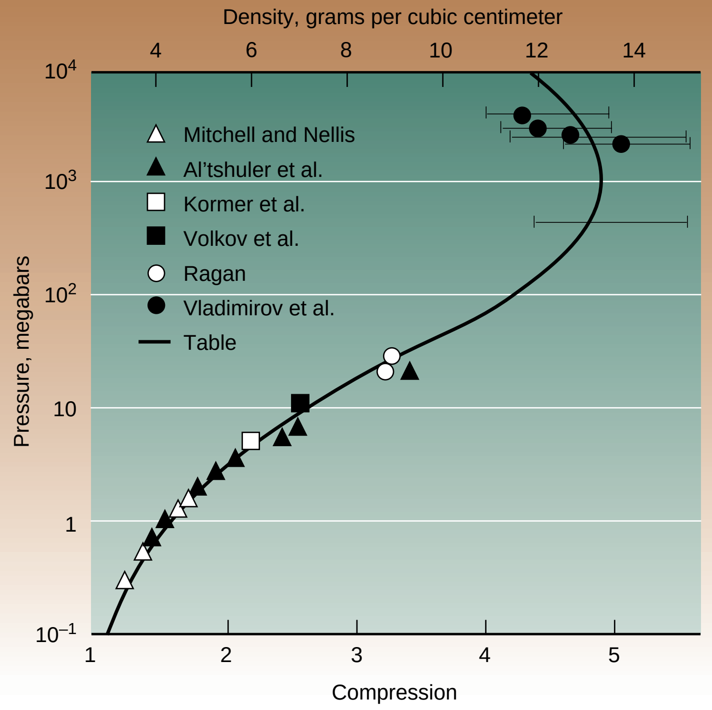
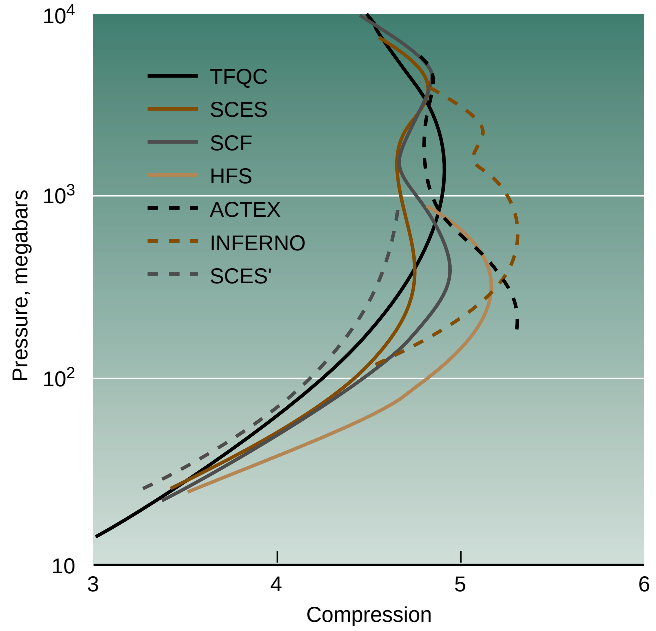


Figure 5. Comparison of experimental and theoretical shock Hugoniots of aluminum. The data points at the upper, highest pressure portion of the graph come from experiments conducted in Soviet nuclear weapons tests and reported in the open literature.

Figure 6. Calculations of the principal Hugoniot of aluminum using a variety of theoretical methods, plotted for high pressure and compression, where the various models exhibit differences: Thomas–Fermi model with quantum corrections (TFQC), semi-classical equation of state (SCES), self-consistent field (SCF), Hartree–Fock–Slater (HFS), ionization equilibrium plasma (ACTEX), INFERNO, and another version of the semi-classical equation of state (SCES').



for aluminum. Potentially, powerful lasers can provide experimental data to fill in the curve, not only for aluminum but for many other materials.

For each point on the Hugoniot, scientists must measure two quantities. One is usually the speed of the shock in the material. Another can be the speed to which the shocked material has been accelerated, the so-called particle speed. To measure shock-wave and particle speeds, scientists use a technique called x-ray backlighting. A shock can be driven into a material with a laser. A beam of x rays generated by a second laser with well-known and closely controlled characteristics illuminates the target from the side. Material changes caused by the shock wave absorb the x-ray backlight differently as it passes through the target. Captured on film, these differences provide the data required to compute points on the Hugoniot.

To measure the principal Hugoniot, the target material at standard temperature and pressure is struck with single shocks of different strength. Measuring the thermodynamic states created when single shock waves pass through the target material gives scientists a set of data points that lie on the principal Hugoniot, which they can then plot. Figure 7 illustrates a recent Nova experiment to measure thermodynamic states. The target had two parts: a flat, very thin plastic "piston" and a wafer of the compound under study. Laser-generated x rays launched a strong shock, several tens of megabars, into the piston, sending a shock wave through the wafer.

Another measurement technique, impedance matching or shock breakout, relies on comparing shock velocities in a reference material of known characteristics (often aluminum) with those in a test sample. Laser-generated x rays or a laser-accelerated flyer plate shocks the target, which comprises precisely measured thicknesses (called steps) of the test sample alongside reference material.

Diagnostic instruments record the time it takes the shock wave to break through the opposite faces of the steps, thereby determining the shock speed in both materials. Comparing the test sample with the known standard yields information on the equation of state of the sample.

Uncertainties in important details can complicate interpretation of the results of equation-of-state experiments. Was an absolutely planar shock delivered to the target? Could electrons or radiation from the hohlraum have affected the target before the shock arrived? Despite such challenges, lasers offer the only path currently available for such investigations at pressures greater than 10 megabars, where many theoretical uncertainties linger.

Turbulent Fluid Movement

In contrast to the smooth, orderly behavior of fluids in laminar flow—as visible in a candle flame—rapidly moving fluids tend to become turbulent, the kind of chaotic, disordered state of flow seen in rocket exhausts. Turbulence in swiftly flowing fluids promotes their mixing, such as where fluids of different density border each other.

Scientists study three types of turbulent mixing observed in nuclear weapons: acceleration-induced, when a lighter fluid pushes against a denser fluid (known as the Rayleigh–Taylor instability); shock-induced, when a shock wave passes through the fluid interface (Richtmyer–Meshkov instability); and shear-induced, when two fluids in contact are moving relative to each other (Kelvin–Helmholtz instability). Turbulent mixing is a factor in understanding the operation of both the primaries and secondaries of nuclear weapons.

Experiments on Nova have begun to measure the growth of Rayleigh–Taylor instability in solids. Mounted in a hohlraum, a foil of copper or molybdenum is compressed and shocked while maintained below its melting point. Only after the drive ceases and the metal decompresses does the foil melt, and only then does Rayleigh–Taylor instability appear to develop normally. In other words, the strength of the compressed metal stabilizes the interface. These experiments are directly relevant to primaries, where materials retain strength throughout much of the explosion.

In the familiar low-energy-density world, most fluid flows behave as if incompressible. But weapon physics must deal with the compressible flows that exist under conditions of high energy-density. Understanding the effects of compressibility and radiation flow on hydrodynamic mixing is crucial. Compressibility alters density, affecting the evolution of perturbations and the behavior of mixing.

A recent Nova experiment has investigated turbulent mixing caused

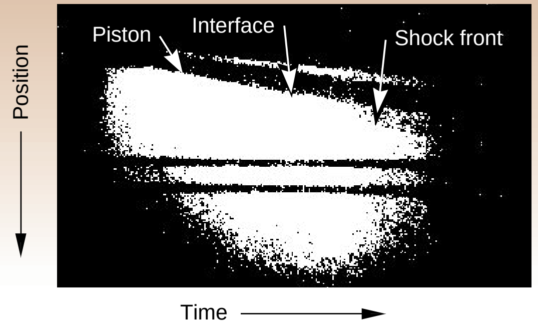


Figure 7. Initial results from an experiment using the Nova laser to measure the equation of state of a plastic. The time-resolved one-dimensional image shows the interface between a plastic piston (doped with bromine to make it opaque to the x-ray backlighter) and the undoped plastic sample being compressed . Note the shock front moving ahead in the plastic.

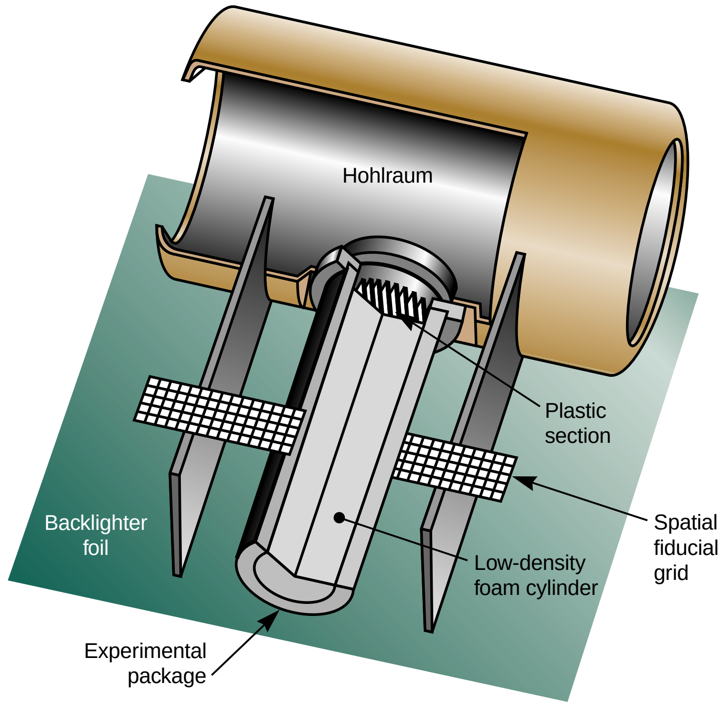


Figure 8. Cutaway view of the hohlraum and attached experimental package for measuring shock-induced mixing. Within the beryllium shock tube is the plastic section with machined sawtoothed perturbations and the low-density foam cylinder. Behind the experimental package is the backlighter foil.

by shock-induced Richtmyer–Meshkov instabilities in an environment of high energy-density. The experimental package comprised a beryllium tube mounted perpendicularly to the side of a standard Nova hohlraum (Figure 8). Within the tube nearest the hohlraum was a plastic section, beyond which was a cylinder of low-density foam.

Rapidly heated to very high temperature by the focused laser beams, the hohlraum launched a shock into the plastic. Upon crossing the sawtooth-shaped interface between plastic and foam, the shock induced a mixing flow (Figure 9a). Experimental results agreed well both with simulations and a theoretical model (Figure 9b).

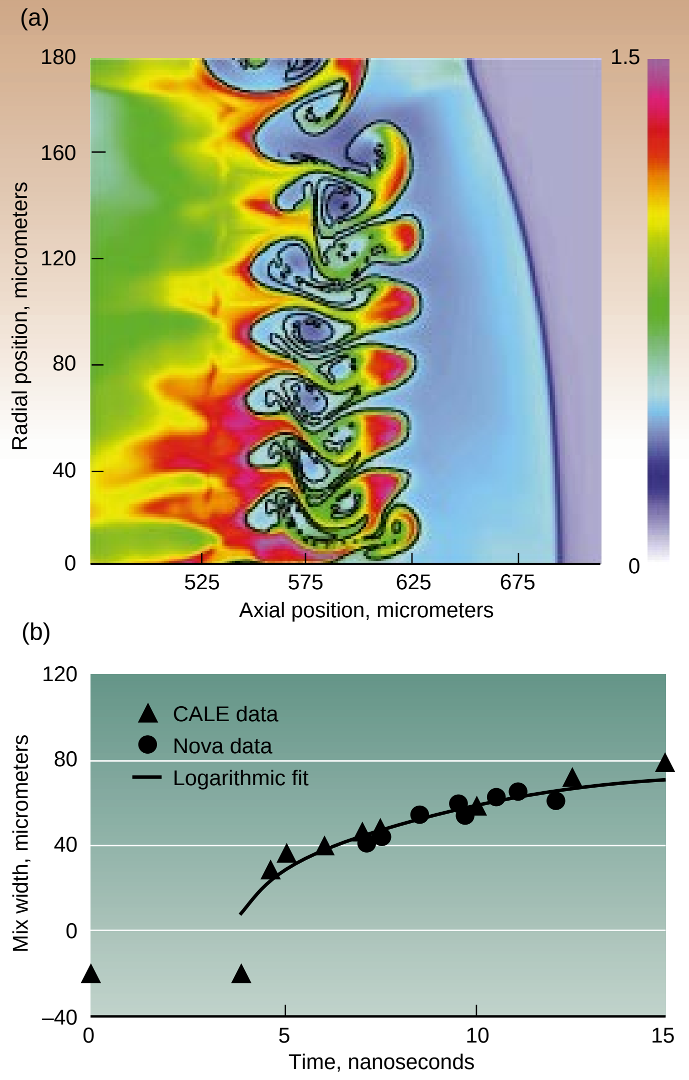


Figure 9. (a) Mixing flow showing density and material contours 7.5 nanoseconds after shock delivery, as modeled by the two-dimensional CALE computer code. (The bar to the right is the logarithm of density.) (b) The width of the mixing region evolves logarithmically with time. The circles represent measured widths from Nova experiments; the triangles represent data points calculated using the CALE code. Good agreement between experimental data and numerical simulation promotes confidence in the code.

Figure 10 compares three-dimensional surface plots created from data from a recent Nova experiment with a three-dimensional simulation of the event created by the HYDRA three-dimensional simulation code.[4] Both representations show a broad bubble surrounding narrow spikes, a shape characteristic of the nonlinear phase of the Rayleigh–Taylor instability. The HYDRA simulation reproduces not only the overall magnitude of the perturbation, but essentially all of the details of the shape, and demonstrates the Laboratory's unique ability to accurately model in three dimensions nonlinear aspects of high-energy-density experiments.

Other Nova experiments are under way, and still others are planned. Nova-class lasers can routinely achieve extreme accelerations, pressures of hundreds of megabars, rapid growth of turbulence, great compression, and high levels of radiation flow and ionization. Powerful lasers can, within certain limits, produce energy-densities that approximate a very-small-scale nuclear detonation.

Opacity and X-Ray Transport

Materials vary in the degree to which they absorb and re-emit radiation of given wavelengths under given conditions, directly affecting the passage of radiation through them. The material's opacity is defined as the measure of how easily it can transmit radiation. Because x rays transport much of the energy in a nuclear weapon, weapon physics is concerned particularly with opacities at x-ray wavelengths.

In the high-temperature plasmas created by nuclear detonation, atoms become highly ionized and the number of possible atomic transitions grows very large. The complicated interaction of radiation with these complex ions makes opacity hard to calculate and forces scientists to rely on approximations. To test such approximations, they have conducted experiments on many different materials at various temperatures and densities. Comparing these data with code calculations can then improve both physical models and computer simulations of opacity.

Because opacity varies rapidly with sample conditions, experiments demand accurate measurement not only of opacity but also of temperature and density. Scientists can obtain such highly precise measurements only if the sample's temperature and density are spatially uniform. Over the past several years, they have devised techniques for doing so within laser-produced plasmas. In a typical experiment, an opacity sample doped with a tracer material with a low atomic number (e.g., aluminum) is sandwiched between layers of plastic and put into a hohlraum. Laser-generated x rays heat and ionize the sample. Constrained by the plastic, the sample expands uniformly and so maintains a constant density.

X-ray backlighting, basically similar to backlighting techniques described earlier, probes the target to provide the required measurements. Two x-ray backlight sources are used. X rays from one backlighter pass through the sample to an x-ray spectrometer, which measures the transmitted spectrum to give the opacity. An experimental setup is shown schematically in Figure 11. The spectrometer also records the absorption spectrum of the tracer material. From the degree of tracer ionization, the sample's temperature can be determined to better than 5% accuracy. The other backlighter illuminates the sample from the side, allowing the width of the expanding sample to be measured and its density to be computed. Figure 12 compares opacity data obtained with the Nova laser with results obtained using a new opacity code.

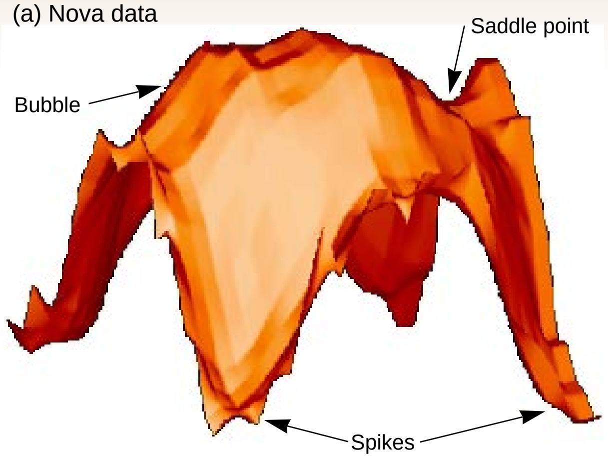
Other Nova Experiments

Opacity alone will not suffice to calculate radiative processes in a weapon. Scientists also require detailed physical models of heat transport and must understand interactions between radiation and matter. Radiative heat and particle transport experiments truly of value to weapon scientists working on stockpile stewardship demand more laser energy than Nova can furnish. Preliminary experiments on Nova, however, have helped develop research techniques and increase understanding of the basic physics in this area.

In one type of experiment, a thin opaque foil replaces part of the hohlraum wall. Laser-generated x rays inside the hohlraum blow off the foil's inside surface, driving a shock back into the foil. The shock traverses the foil and breaks out its back surface. An ultraviolet telescope, coupled with an optical streak camera, is focused on the foil's back side to measure the time of shock breakout, from which the temperature inside the hohlraum can be inferred.

The radiation field inside the hohlraum also drives a radiative heat wave through the shocked foil material. The breakout of this heat wave on the foil's back side is recorded by a streak camera. By using different types and

(a) Nova data



(b) HYDRA simulation

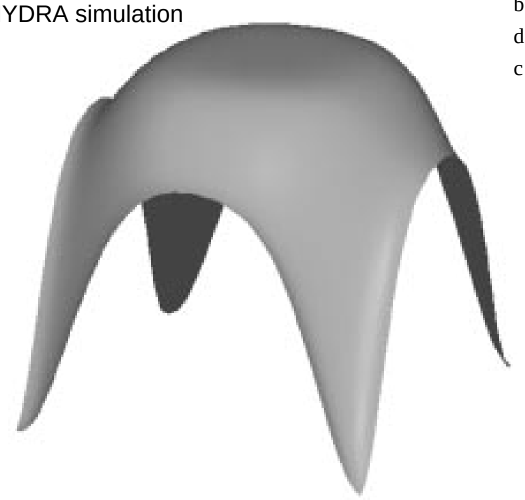


Figure 10. Comparison of (a) the three-dimensional surface plot of data from a Nova experiment 4.3 nanoseconds after shock delivery with (b) a three-dimensional simulation of the event using the HYDRA computer code shows an excellent correlation between experimental data and code calculation.

thicknesses of foils, scientists can attempt to understand the different effects of opacity, temperature drive, and radiative heat transport.

In a similar type of experiment, a thick sample of low-density foam replaces the thin foil. At low enough densities, the heat front will precede the shock front, permitting scientists to study heat transport through unshocked material. This type of experiment also allows viewing the sample from the side; x-ray backlighting techniques allow the shock position through the sample to be measured as a function of time. This technique gives a great deal more information than the simple shock breakout experiment.

Not all physics experiments fall neatly into the categories of radiation and hydrodynamics. Some are designed to be so complex that they must be modeled with computer codes that take into account the full range of hydrodynamic and radiative processes that would formerly have been involved in a nuclear test. These so-called integrated experiments are intended to validate the integrated physical model and to test the scientist's ability to model extremely complex behavior. Other experiments supported by the weapons program aim at developing diagnostic techniques. Still others are directed toward enhanced understanding of basic science.

One set of experiments that began as basic scientific inquiry resulted in a very useful diagnostic tool—x-ray lasers. Intense brightness, narrow bandwidth, small source size, and short pulses give x-ray lasers many advantages over conventional x-ray illumination devices as imaging systems for experiments not only in physics, but also in inertial confinement fusion and biomedicine.

The Value of NIF

Over a decade of operation has proved the Nova laser's value in studying weapon physics. Nova experiments have already helped improve computer codes through better knowledge of processes like turbulent mixing and properties like x-ray opacity. In the future, such experimentally based knowledge will matter even more. The ability to tie these experimental data back to the simulation codes is crucial for stockpile stewardship.

When nuclear testing was an option, scientists' inability to calculate every detail precisely hardly mattered. They could determine what happened by diagnosing an actual detonation. With that option gone, however, the ability to calculate the effects of each detail, some not calculated at all in the past, assumes major importance. Doing so requires new computer codes, which must then be verified by experiment.

Useful though Nova has been, it lacks the power to meet the future data needs of nuclear weapons scientists. Its energy comes up short in some aspect of every research area. In equation-of-state experiments, Nova cannot reach high enough pressures. In hydrodynamic instability experiments, it cannot follow instabilities long enough. In x-ray opacity experiments, it cannot attain high enough temperatures. In radiative heat transport experiments, it falls short in temperature and cannot drive the radiation far enough. Overcoming these limits will become possible with the National Ignition Facility.

Although more powerful lasers like NIF will open wider vistas on weapon physics, they remain some years away. Meanwhile, Nova experiments have already provided laboratory access to physical phenomena once thought obtainable only by full-scale nuclear tests. With field-testing ended, they have enabled scientists from all the weapons laboratories to continue improving codes through enhanced knowledge of such basic processes as equations of state, mixing, and radiation opacity.

In coming years, Nova will continue to demonstrate, as it has for more than a decade, that in studying the physics of nuclear detonation, powerful lasers can, at least in part, provide code validation data formerly derived from underground nuclear tests.

—Bart Hacker

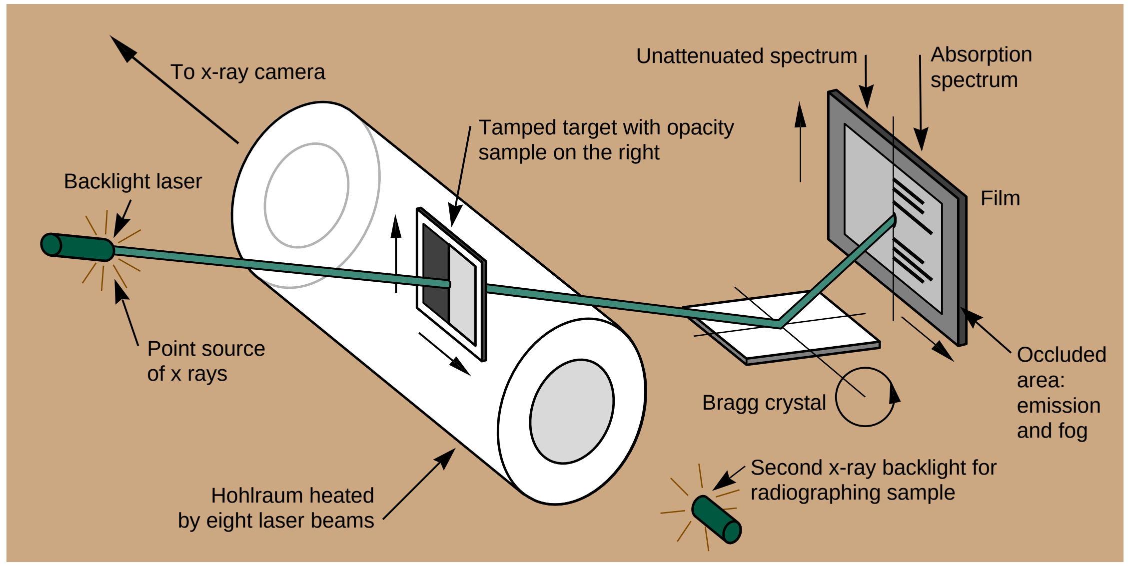


Figure 11. Schematic of point-projection spectroscopy for opacity measurements. The laser-produced backlight x rays are imaged after passing through the target. The image is spatially resolved by a Bragg crystal, while temporal resolution is provided by backlight duration.

Key Words: equation of state, Hugoniot, hydrodynamic instability, National Ignition Facility (NIF), Nova laser, opacity, radiative heat transfer, Stockpile Stewardship and Management Program, weapons physics.

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3. E. Michael Campbell et al., "The Evolution of High Energy-Density Physics: From Nuclear Testing to Superlasers," Lawrence Livermore National Laboratory, Livermore, California, UCRL-JC-124258, Rev. 2 (July 1997). This article is scheduled to appear in *Laser and Particle Beams* **15**(4) (December 1997).
4. M. M. Marinak et al., "Three-Dimensional Single Mode Rayleigh–Taylor Experiments on Nova," *Physical Review Letters* **75**(20), 3677–3680 (November 1995).

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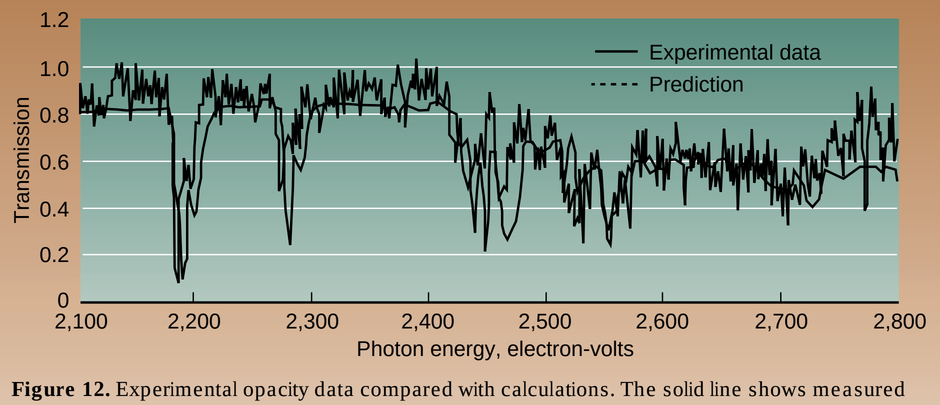
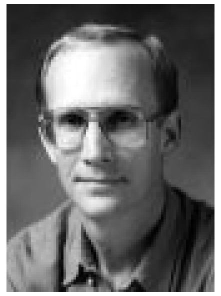


Figure 12. Experimental opacity data compared with calculations. The solid line shows measured x-ray transmission through a niobium sample. The dashed line shows the similar results calculated using an opacity code recently developed at Livermore. Good agreement with experimental data bolsters confidence in the opacity calculations and their underlying theory.

About the Scientists

TED PERRY holds a B.S. in mathematics and physics and an M.S. in mathematics from Utah State University. He also did graduate work at Princeton University, where he received an M.A. and Ph.D. in physics. He joined Lawrence Livermore National Laboratory in 1981, and between 1981 and 1991, he worked in the nuclear test program at the Laboratory, performing experiments on seven underground nuclear tests. In 1991, he became one of the program leaders for weapons physics experiments in A Division of the Defense and Nuclear Technologies Directorate. His recent work has focused on weapon physics experiments using the Nova laser. Hereceived the Department of Energy's Excellence in Weapons Research Award in 1985 and 1994.



BRUCE REMINGTON received a B.S. in mathematics from Northern Michigan University in 1975 and a Ph.D. in physics from Michigan State University in 1986. He joined the Laboratory as a postdoctoral associate in 1986 doing nuclear physics research and became a permanent staff physicist in the Laser Programs Directorate in 1988. Currently as leader of the hydrodynamics group of the Inertial Confinement Fusion Program, he initiates and manages direct- and indirect-drive hydrodynamics experiments on the Nova laser related to high- energy-density regimes, compressed solid-state regimes, fluid dynamics, and astrophysics.