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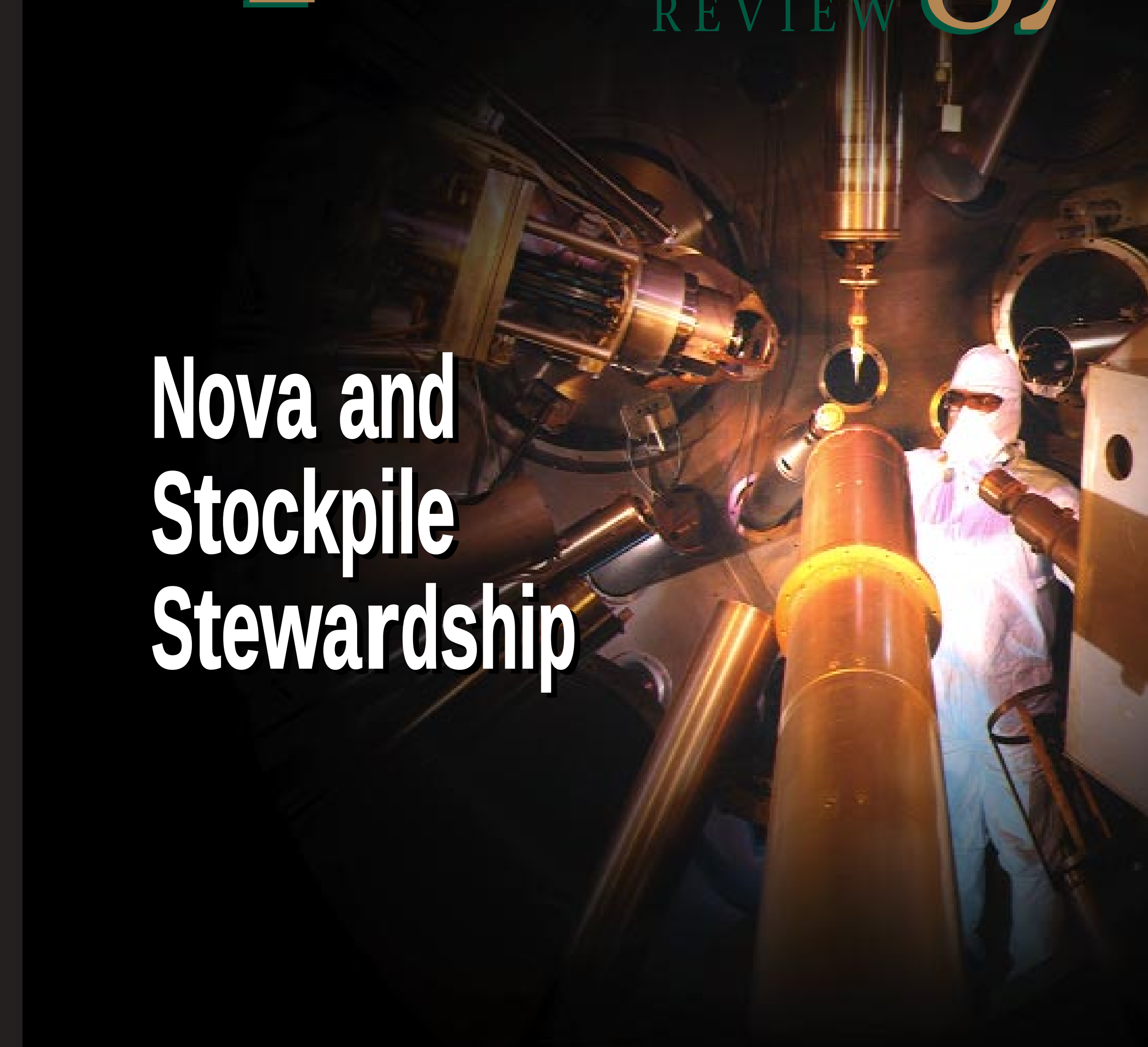

Nova and Stockpile Stewardship

Also in this issue:

- **Collaborations to Reduce Proliferation Risks**
- **Taming Explosives for Training**

About the Cover

Lawrence Livermore's Nova laser remains, until the National Ignition Facility is completed, the world's largest laser. It has been and continues to be a rich source of experimental data about the behavior of matter at pressures and temperatures approaching those of an exploding nuclear weapon, but on a minute scale. In an era when nuclear testing is no longer an option for gathering data about the precise nature of nuclear weapons detonations, Nova is proving to be a valuable tool in helping to determine the safety and reliability of the nation's nuclear stockpile. The article beginning on p. 4 reports on Nova's contributions to DOE's Stockpile Stewardship and Management Program. The cover shows a Laboratory technician working inside the Nova target chamber where ten arms deliver 40,000 joules of laser energy to a half-millimeter-diameter target.

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About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published ten times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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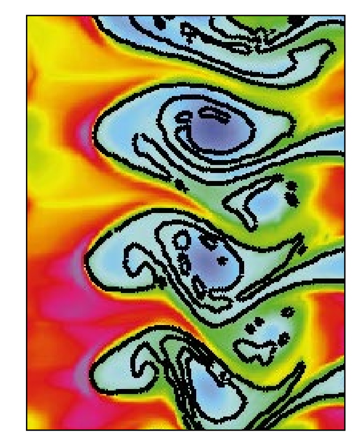
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Lawrence Livermore Breaks Ground for NIF

Energy Secretary Federico Peña joined Laboratory Director Bruce Tarter and Congresswoman Ellen Tauscher on May 29 to break ground for the National Ignition Facility. Speaking to a gathering of more than 2,000 employees and guests, Peña called NIF "one step closer to a better future" and concluded that "NIF will unleash the power of the heavens to make Earth a better place."

The new $1.2-billion facility will house a 192-beam laser, the world's largest. Through NIF, Lawrence Livermore and other national laboratories will work to achieve fusion energy as well as help assure the safety and reliability of the nuclear stockpile without nuclear testing.

Peña's praise of the Laboratory's scientific achievements was echoed by Tauscher, Tarter, Assistant to the Secretary of Defense Harold Smith, University of California President Richard Atkinson, and Livermore Mayor Cathie Brown.

Smith said that NIF underscores the importance of the collaborations between the national laboratories and the Department of Defense. "NIF marks a creative step toward meeting the needs of national security," he said.

Atkinson pointed out that the nation's universities account for more than a quarter of federally funded research in the nation. Through NIF, he sees even greater collaborations between UC institutions and the national laboratories.

Tauscher called the NIF groundbreaking "a testament to the Lab's hard work." She also believes NIF will be an excellent example of how the national laboratories will work with the private sector to develop an alternative energy source as well as future technologies.

Brown said the City of Livermore was most fortunate to be the home of two unique national laboratories. Calling Lawrence Livermore "a key stakeholder in our community," she thanked the Laboratory's employees for "leadership in science, engineering, national security, environmental quality, education, and job growth."

The National Ignition Facility is scheduled to be completed in 2003.

Contact: LLNL Media Relations (510) 422-4599 (garberson1@llnl.gov).

Lawrence Livermore Wins Seven R&D 100 Awards

When researchers who won coveted R&D 100 awards sit down at the awards banquet in Chicago this month, Lawrence Livermore will be well represented. The Laboratory's seven awards this year match its previous record totals, which were set in 1987 and 1988. Since 1978, the Laboratory has won 68 of these awards, which are considered to be the "Oscars" of the research and development community.

Each year, *R&D Magazine* honors the top 100 entries to the competition with this prestigious award. Three other Department of Energy national laboratories won awards: Sandia and Oak Ridge each won eight, and Los Alamos won six.

The Lawrence Livermore winners are:

- **Absolute Interferometer**, by a team led by Gary Sommargren of the Laser Programs Directorate. This invention super-accurately measures large surfaces to atomic dimensions (less than a billionth of a meter). This capability, a hundredfold increase over previous technology, will expand the frontiers of the semiconductor and optical manufacturing industries and be invaluable in making tools for metrology.

Contact: Gary Sommargren (510) 423-8599 (sommargren1@llnl.gov).

- **Ultraclean Ion Beam Sputter Deposition System**, by a team headed by Stephen Vernon of the Laser Programs Directorate. This system deposits ultralow-defect thin films on substrates, reducing defects by a factor of 100,000. These virtually defect-free films are critical to device fabrication in the $120-billion semiconductor industry and the $100-billion magnetic recording industry.

Contact: Stephen Vernon (510) 423-7826 (vernon1@llnl.gov).

- **Femtosecond Laser Materials Processing**, by a team headed by Brent Stuart of the Laser Programs Directorate. This new machining tool uses lasers to machine all materials, regardless of composition (steel, diamond, heart tissue, etc.) with negligible heat and damage to collateral materials. It uses pulses that are of so short a duration that material even within 0.1 micrometers of the machined surface is not damaged. The method enables a new class of high-precision machining, with applications ranging from surgery to demilitarization of chemical, biological, and nuclear weapons components.

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(continued on page 28)

Superlasers as a Tool of Stockpile Stewardship

DRAMATIC changes in U.S. nuclear weapons policy have followed the end of the Cold War, among them halts to the development of new types of weapons and to weapon testing. The current stockpile must remain safe, secure, and reliable into the indefinite future as it undergoes changes caused by aging or remanufacturing and replacement of aging components. This challenge has led to the development by DOE of the Stockpile Stewardship and Management Program. Henceforth, confidence in America's nuclear arsenal will depend more than ever on our fundamental understanding of weapon science and technology. That understanding must now be pursued without recourse to system-level tests of integrated performance—the detonation of full-scale nuclear devices.

Scientists have turned to several tools, including advanced hydrotesting, subcritical experiments, advanced computer simulation and modeling, and what have come to be called superlasers, to address some of the remaining scientific issues. Nuclear detonations produce enormous total energy; no laboratory tool can deliver more than a small fraction of nuclear yield. But nuclear detonations also produce very high levels of energy per unit volume, that is, high energy density. High-power lasers 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. They also can permit the production and study of fusion ignition in the laboratory.

As a result of superlasers and other laboratory tools, the study of high-energy-density physics can be moved from the Nevada Test Site to the laboratory, at least in part. Doing so can offer some real advantages. High-power lasers can support more frequent experiments than full-scale weapon testing could. They also offer more precise control of experimental conditions and greater access for detailed measurements; that is, the variables can, to some extent, be separated. These capabilities contribute significantly to the feasibility of stockpile stewardship and management.

The development of high-power lasers has enhanced the ability to pursue basic research on nuclear detonation. Since 1985, weapon scientists from various laboratories have used the Nova laser system to conduct more than 12,000 experiments. Even as Nova research continues, preparations are under way for its successor; the National Ignition Facility will become a cornerstone of DOE's Stockpile Stewardship and Management Program.

Although ten times more powerful and forty times more energetic than Nova, NIF will still produce total energies only a tiny fraction of those in full-scale nuclear detonations—total energy in the laser beams will be equivalent to a half pound of TNT, or one billionth of the energy of a nuclear weapon. Yet NIF will be able to approach much more closely than Nova the range of high energy-densities (and therefore temperatures) produced by nuclear weapons and necessary to achieve fusion ignition. With NIF, many of the fundamental processes of thermonuclear detonation become, for the first time, fully accessible to laboratory study and analysis. As a bonus, NIF will provide a unique means of testing nuclear weapon effects and a powerful new tool for basic science applications of high-energy-density physics (e.g., astrophysics, plasma physics, and fusion energy).

The next generation of superlasers, such as NIF in the United States and the French Laser MegaJoule (LMJ), will provide still more detailed understanding of the processes of nuclear detonation. It will enable scientists to gain a much improved understanding of the basic physics of nuclear weapons, greatly enhance their ability to predict weapon performance, and provide a sounder basis for assuring the safety and reliability of the nuclear stockpile.

■ E. Michael Campbell is Associate Director, Laser Programs.

■ Michael Anastasio is Associate Director, Defense and Nuclear Technologies.

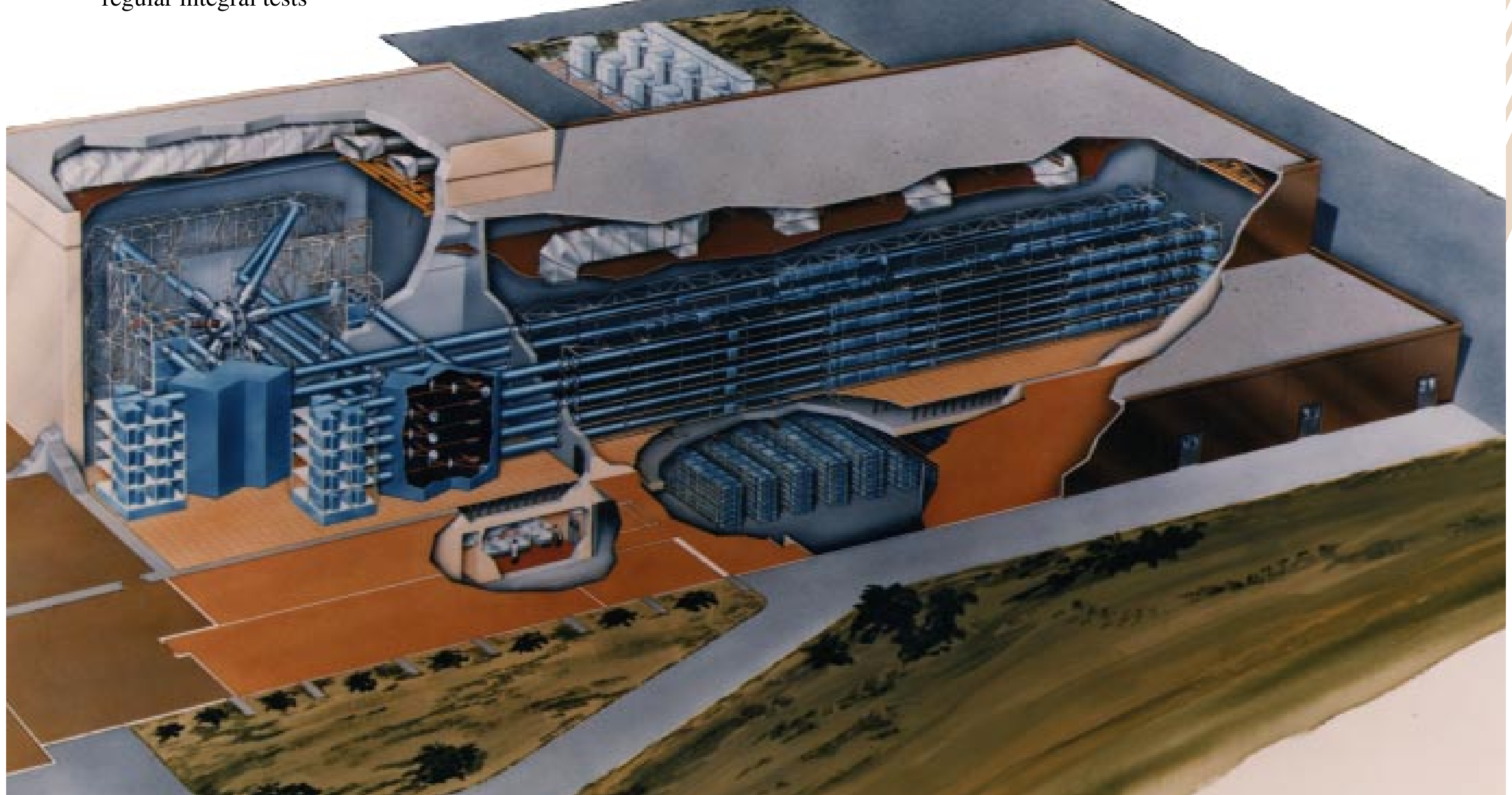
Nova Laser Experiments and Stockpile Stewardship

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.

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).

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 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.

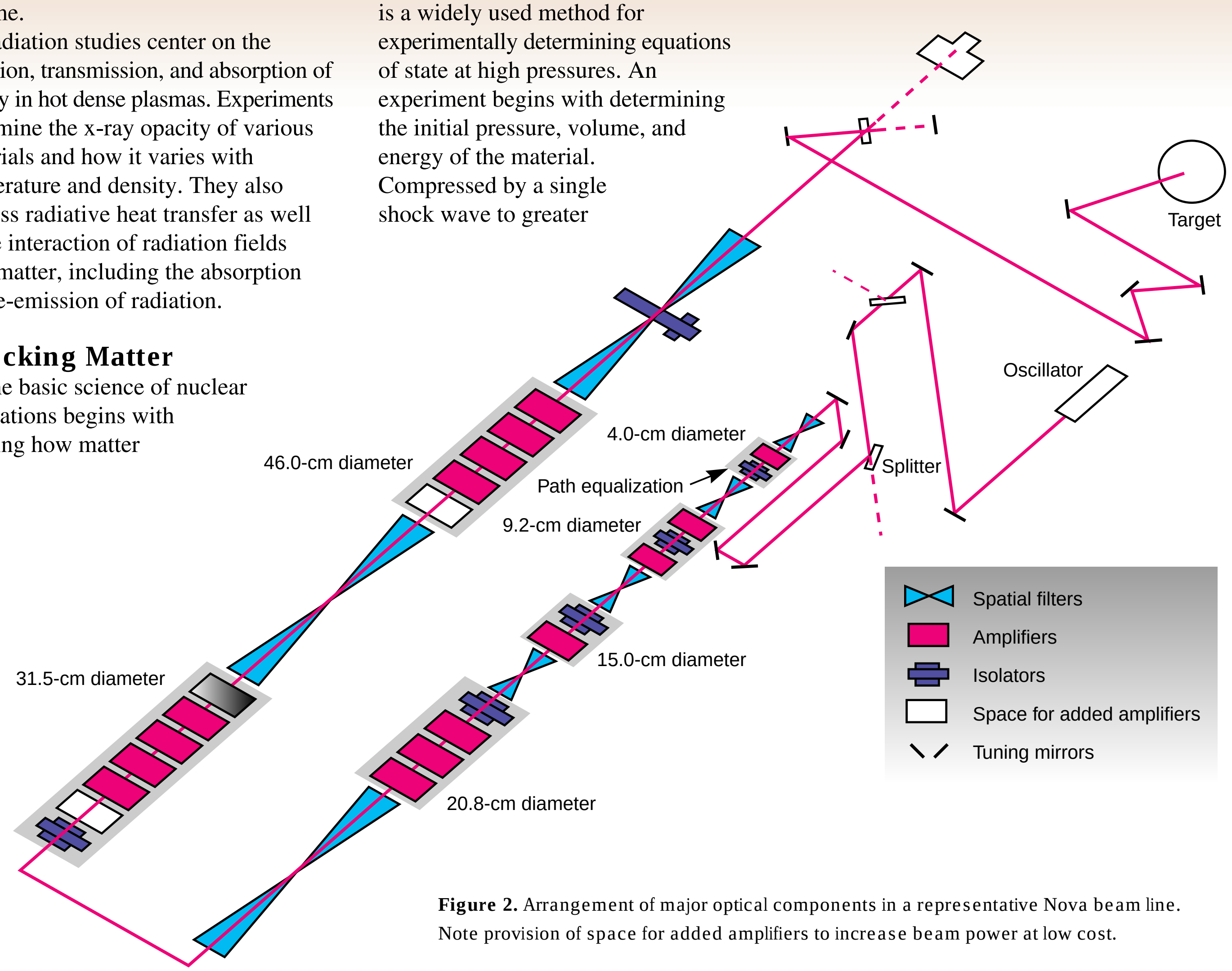


Figure 2. Arrangement of major optical components in a representative Nova beam line. Note provision of space for added amplifiers to increase beam power at low cost.

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

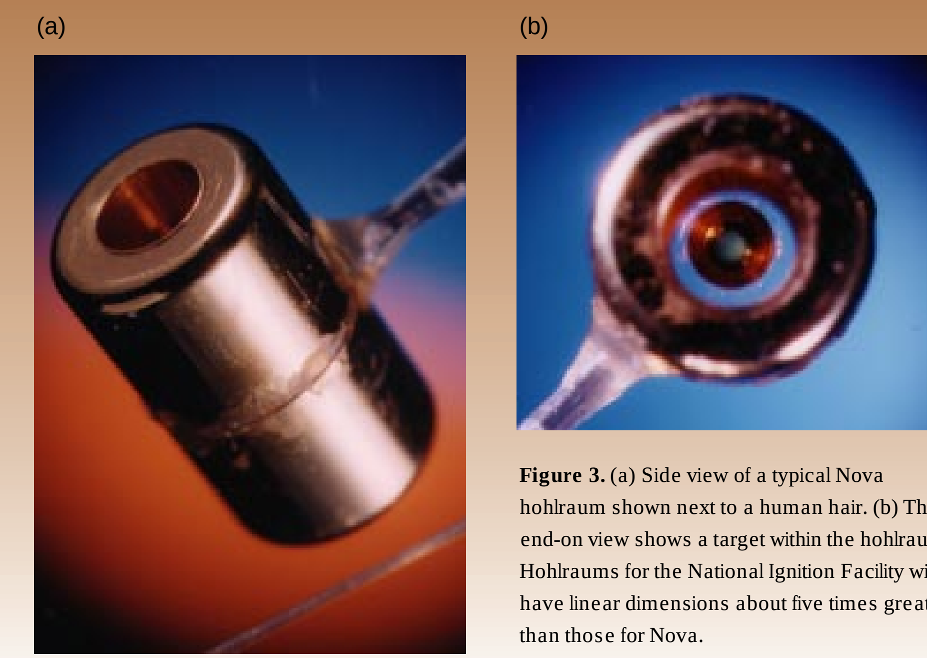


Figure 3. (a) Side view of a typical Nova hohlraum shown next to a human hair. (b) The end-on view shows a target within the hohlraum. Hohlraums for the National Ignition Facility will have linear dimensions about five times greater than those for Nova.

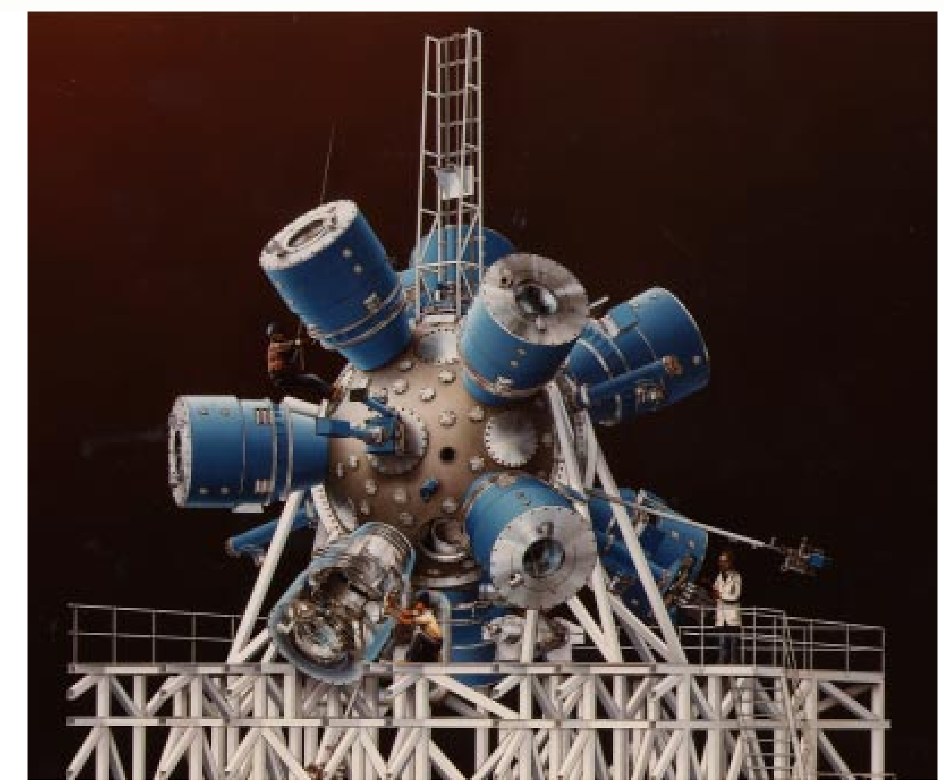


Figure 4. Artist's rendering of the outside of the Nova target chamber, where the ten laser beams converge to heat and shock a tiny hohlraum. Note the two human figures at work on the platform. The entire structure is three stories high, and the spherical target chamber is 4.5 meters (15 feet) in diameter.

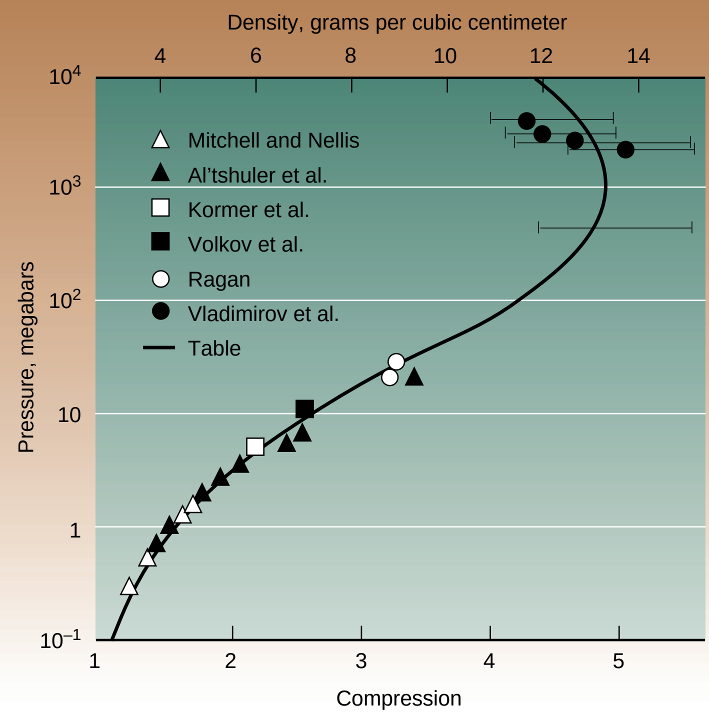
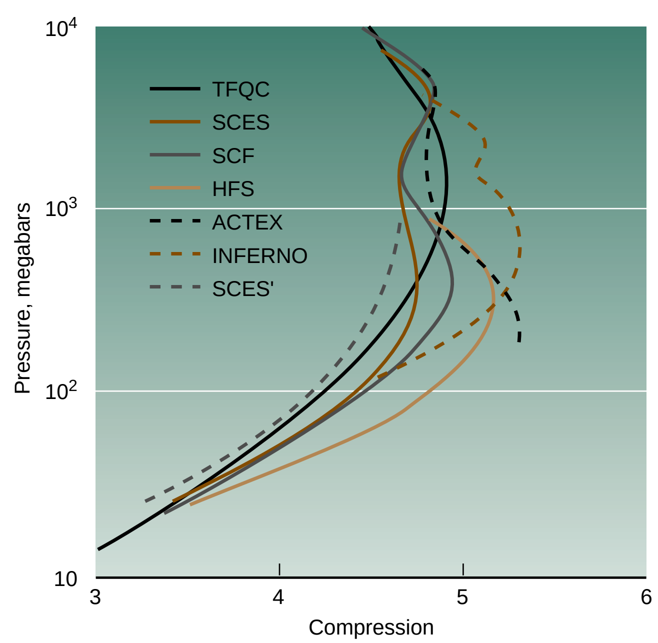


Figure 5. Comparison of experimental and theoretical shock Hugoniots of aluminum. The data points at the upper, highest pressure portion of the graph come from experiments conducted in Soviet nuclear weapons tests and reported in the open literature.

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

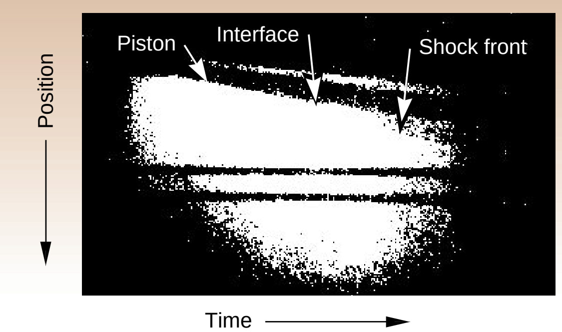


Figure 7. Initial results from an experiment using the Nova laser to measure the equation of state of a plastic. The time-resolved one-dimensional image shows the interface between a plastic piston (doped with bromine to make it opaque to the x-ray backlighter) and the undoped plastic sample being compressed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

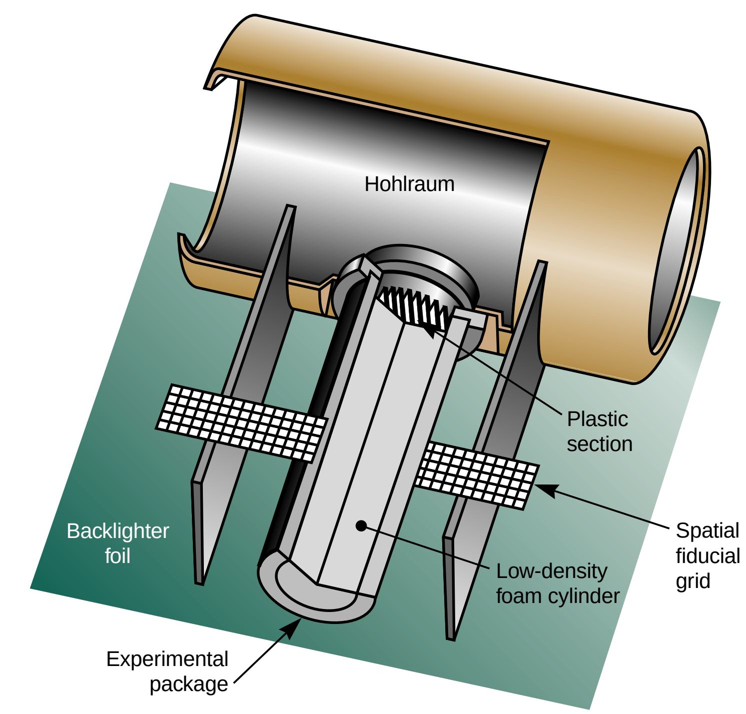


Figure 8. Cutaway view of the hohlraum and attached experimental package for measuring shock-induced mixing. Within the beryllium shock tube is the plastic section with machined sawtoothed perturbations and the low-density foam cylinder. Behind the experimental package is the backlighter foil.

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).

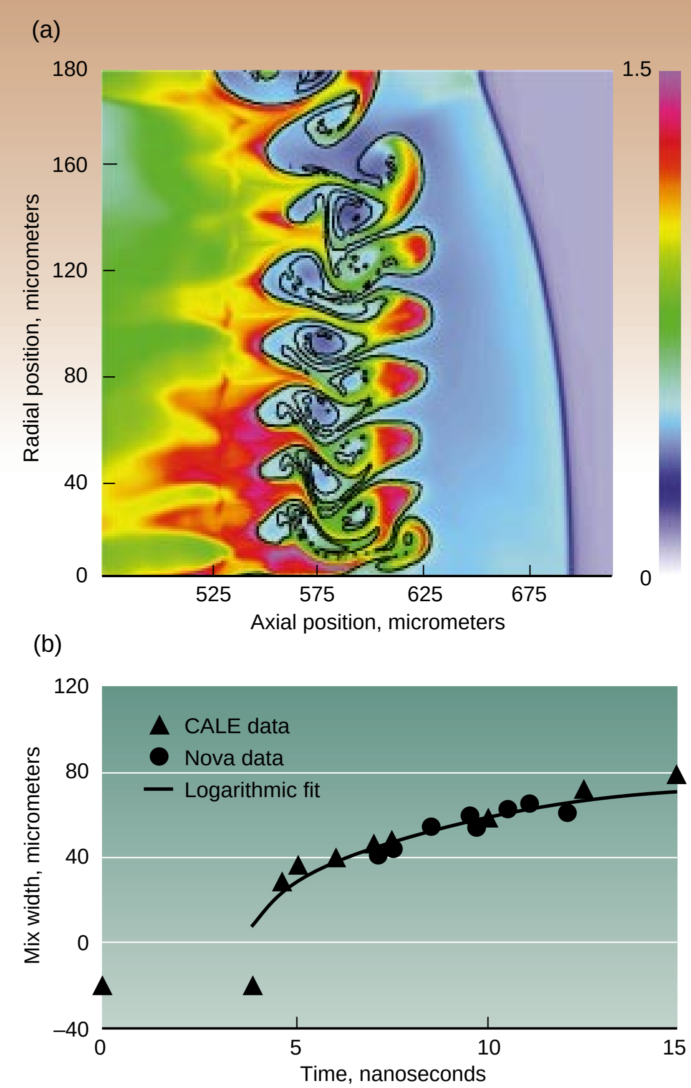


Figure 9. (a) Mixing flow showing density and material contours 7.5 nanoseconds after shock delivery, as modeled by the two-dimensional CALE computer code. (The bar to the right is the logarithm of density.) (b) The width of the mixing region evolves logarithmically with time. The circles represent measured 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

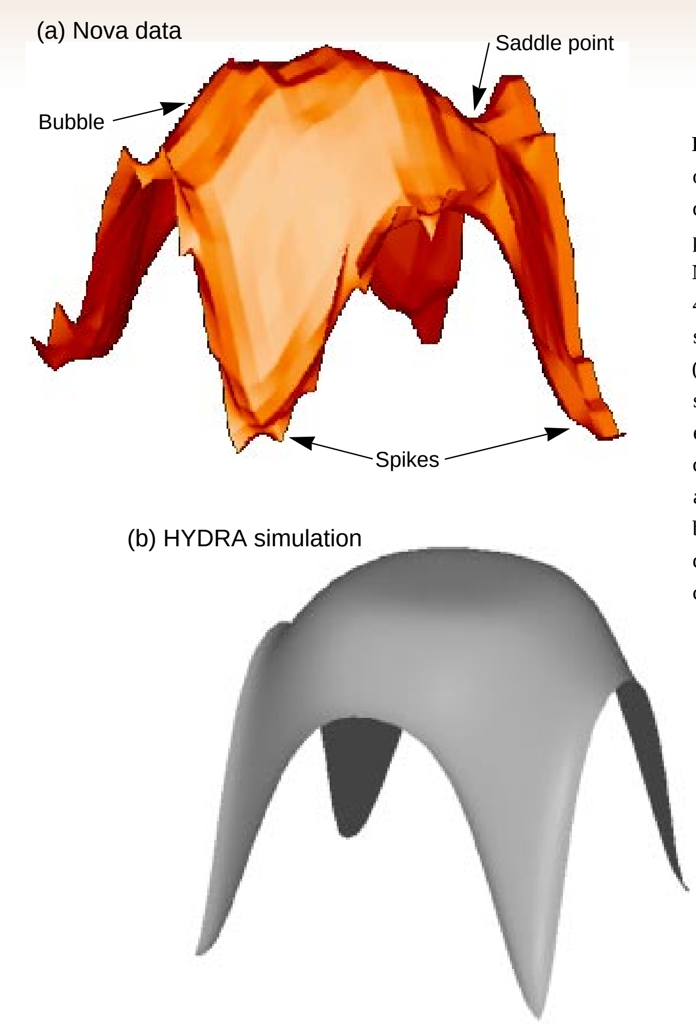


Figure 10. Comparison of (a) the three-dimensional surface plot of data from a Nova experiment 4.3 nanoseconds after shock delivery with (b) a three-dimensional simulation of theat event using the HYDRA computer code shows an excellent correlation between experimental data and code calculation.

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

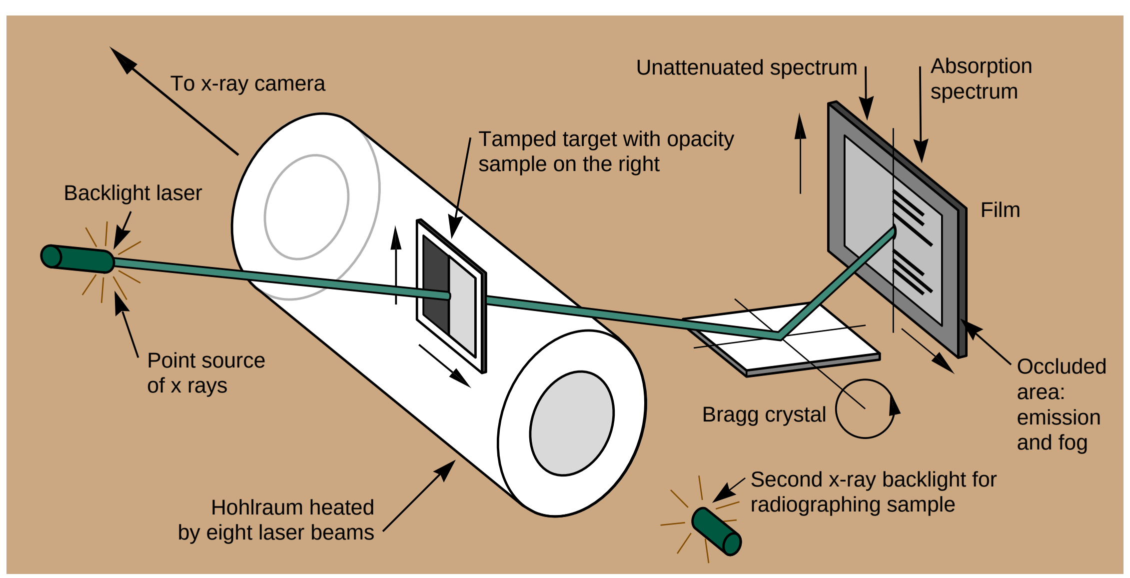


Figure 11. Schematic of point-projection spectroscopy for opacity measurements. The laser-produced backlight x rays are imaged after passing through the target. The image is spatially and spectrally resolved by a Bragg crystal, while temporal resolution is provided by backlight duration.

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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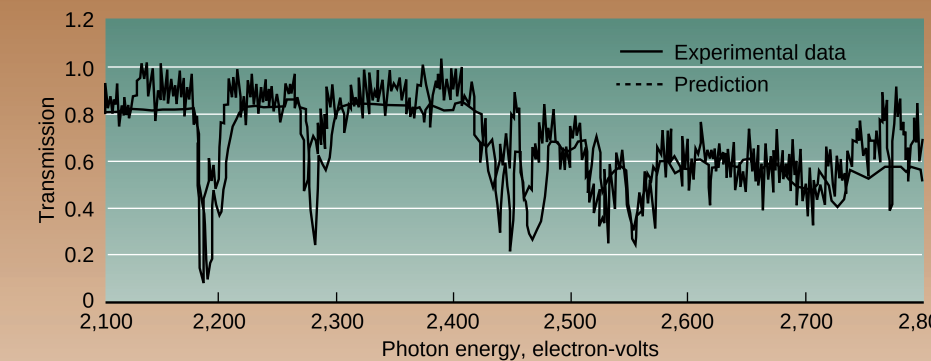
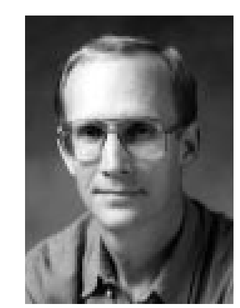


Figure 12. Experimental opacity data compared with calculations. The solid line shows measured x-ray transmission through a niobium sample. The dashed line shows the similar results calculated using an opacity code recently developed at Livermore. Good agreement with experimental data bolsters confidence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

Sharing the Challenges of Nonproliferation

The changes brought about by the end of the Cold War have created a surprising turn of events. Once unthinkable collaborations and partnerships to reduce the threat of proliferation are now happening with increasing frequency.

IN these post–Cold War days, the secret cities that contain Russia's weapons complex remain closed, still surrounded by fences patrolled by armed guards. But changes are going on within them. Scientists and engineers from Lawrence Livermore can now be found inside, engaged in meetings with their Russian counterparts. This change has occurred largely because of the convergence of two events: the shift from an arms race to arms reduction, and the dissolution of the Soviet Union, with its attendant economic upheaval.

One of the many risks introduced by the first event is that of increased nuclear proliferation if the disposition of nuclear weapons technology and materials is not managed carefully. Russia has, for example, large amounts of surplus weapons-grade nuclear materials in various forms. These materials are highly desirable to potential proliferators and terrorists. They have become more vulnerable to theft or diversion because Russia now has fewer resources to apply to safeguarding its nuclear materials. U.S. and Russian scientists and engineers are working together to reduce such risks.

U.S. policy makers recognize that Russian nuclear scientists have essential roles to play in global arms reduction and nonproliferation causes. Alleviating the scientists' economic hardships and uncertainty would greatly aid the stabilization of Russian nuclear weapons complex. To these ends, the U.S. Department of Defense has formulated a policy to aid Russian scientists through stimulating commercial economic development in the closed cities. One large component of the policy is the Nunn–Lugar Cooperative Threat Reduction bill, passed in 1991, which initiated collaborations between the U.S. and the newly independent states (NIS), principally Russia. The effectiveness and positive reception of Nunn–Lugar initiatives led to similar and complementary initiatives by the Energy and State departments.

Dubbed "defense by other means" by former Secretary of Defense William Perry, this policy depends as much on scientific capabilities as on political expertise. Thus, Lawrence Livermore staff have found themselves traveling thousands of miles between Livermore and various parts of the NIS to collaborate with NIS scientists on worthwhile, non-weapons-related projects as well as to monitor and assist the progress of arms reduction.

Livermore technician Lori Switzer (foreground) works with Russian scientists Dmitri Semonov (left) and Mikhail Chernov to evaluate candidate neutron and gamma-ray measurement techniques for mutual reciprocal inspection purposes.

Progress in Arms Reduction

The arms reduction taking place in the U.S. and Russia is an important step for global nuclear security. Because verification activities for the strategic arms reduction treaties (START) are concerned with the destruction of weapons launchers and do not deal with the warheads, the Biden Condition was appended to START I during the ratification process to ensure that warheads would be verifiably dismantled in future arms reduction.

Developing transparency measures to deal with the fissile materials derived from dismantled weapons is the task of the Safeguards, Transparency, and Irreversibility Working Group, a joint effort between the U.S. and Russia. Formed as a result of agreements made between Presidents Clinton and Yeltsin over several summit meetings, the group is chartered with developing mutually acceptable ways to keep fissile materials derived from dismantled nuclear weapons secure, account for and control their quantities, and prevent them from ever being used again in nuclear weapons.

Jim Morgan is one of the Livermore scientists working with this group to implement its complex task. He has been involved in discussions about sharing information on fissile materials. The most difficult negotiations involve key proposals brought to the table by the U.S.:

- Regular exchanges of detailed information about weapons and fissile materials stockpiles.
- Reciprocal inspections at storage facilities to confirm the amounts of plutonium and highly enriched uranium removed from weapons.
- Various arrangements to monitor fissile material stockpiles.

These have been difficult proposals from the beginning, starting with fundamentally differing views on information sensitivity. Russia classifies its information differently than the U.S. In addition, because of former Energy Secretary Hazel O'Leary's openness initiatives, the U.S. has already published some general information about U.S.

(a)

(b)

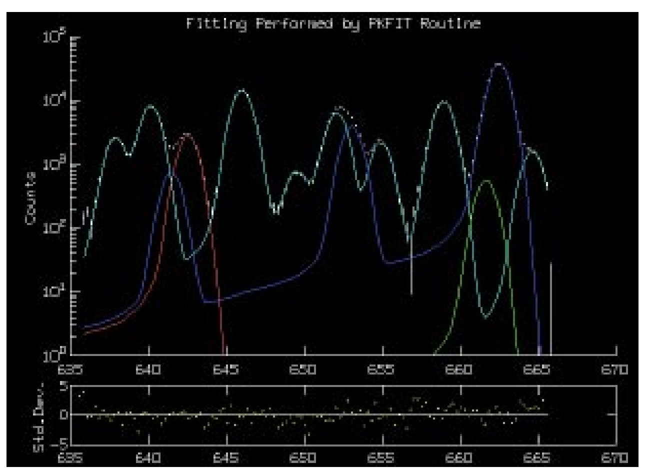


Figure 1. (a) Technician Vern Rekow (left) assists Zachary Koenig in setting up a portable, battery-operated germanium gamma-ray spectrometer. Koenig, a physicist in the Nonproliferation, Arms Control, and International Security Directorate at Livermore, was instrumental in developing this means of determining whether plutonium stored inside containers is consistent with material that may have been plutonium that has been removed from dismantled nuclear weapons. This spectrometer has undergone joint testing with the Russians. (b) Typical results of the spectrometer's reading. The upper plot is a reconstruction of gamma-ray activity, with dots indicating the measured data. Standardized residuals from the gamma-ray activity are plotted below the reconstruction.

fissile materials stockpiles, which goes well beyond the type of information the Russians are willing to share.

The progress of the negotiations has been slow. The U.S. delegation has been trying to maintain some momentum in the talks by suggesting negotiating patterns to keep negotiations moving.

Whatever the course of action, these negotiations will not end when agreements on information exchanges and monitoring procedures have been made. There must also be U.S.–Russian agreements on what measuring devices and instrumentation are allowable for deriving specific information during reciprocal inspections at nuclear facilities.

In parallel to Morgan's work in negotiations, scientists and engineers at Livermore are designing special measuring technologies for use inside U.S. and Russian facilities. One candidate device that has been demonstrated to Russian scientists is a portable, battery-operated, germanium gamma-ray spectrometer. This instrument can determine whether plutonium stored inside containers is consistent with material that may have been removed from dismantled nuclear weapons (Figure 1a). The spectrometer measures the plutonium's gamma-ray intensities in a narrow band of energy (630 to 670 thousand electron-volts) to reveal whether its ratio of plutonium-240 to plutonium-239 is consistent with weapons-grade material; it also estimates what minimum mass of plutonium is necessary to produce the observed intensities (Figure 1b).

The narrow band of energy measured by the spectrometer intentionally leaves some details of the material being measured unknown to satisfy Russian security concerns and make the spectrometer acceptable to the Russians. Tools used for transparency measurements must observe a careful balance between yielding enough to

confirm crucial verification requirements but not revealing so much as to threaten the security interests of either side.

Reducing HEU Holdings

Even as the negotiations for safeguards, transparency, and irreversibility continue, the U.S. has found another way to safeguard some Russian weapons uranium—by buying it. In 1994, the U.S. signed a 20-year, $12-billion deal to purchase 500 metric tons of highly enriched uranium (HEU) recovered from Russian weapons. The contract calls for this uranium to be blended down to low-enriched uranium (LEU) and then shipped to the U.S. to be used for making commercial reactor fuel.

The transparency protocols for the HEU purchase are those that strive, on the one hand, to confirm for the U.S. that the shipped material has indeed been derived from Russian weapons material and, on the other hand, to confirm to Russian satisfaction that the LEU is not going to end up in the U.S. weapons program. These confirmations require access to the uranium processing facilities of both sides. The negotiations for such access, normally complex and difficult, were made even more so when they became subsumed by a host of other issues surrounding the deal, including pricing and LEU market competition.

The final agreement allows Russian monitors access to the U.S. Enrichment Corporation's Portsmouth Gaseous Diffusion Plant in Piketon, Ohio, and to the five U.S. fuel fabrication facilities receiving the Russian uranium. In turn, U.S. monitors are allowed access to the three principal Russian plants involved in the conversion of HEU to LEU. Lawrence Livermore is taking a lead role in support of DOE program activities related to monitoring activities at those three plants.

What the agreement has meant for Livermore's Doug Leich, HEU transparency technical leader and a member of the U.S. monitoring team, is several long trips to Russia each year, to the cities of Seversk, Zelenogorsk, and Novouralsk (Figure 2). At the plant in Seversk, HEU metal is processed into an HEU oxide before being shipped to the electrochemical plants in Novouralsk or Zelenogorsk. In these facilities, the oxide is fluorinated and combined with a slightly enriched blending material to turn it into LEU suitable for making civilian power reactor fuel.

Monitoring Activities

Describing the monitoring tasks at Seversk, Leich says that monitors can observe the whole oxidation procedure, from the beginning when the uranium metal is analyzed by portable gamma-ray spectrometry to confirm its weapons-grade status, through its feed into and withdrawal from oxidation process equipment, to the final analysis of the withdrawn oxides. Leich and the other monitors apply U.S. tags and seals to some containers of the oxides before their shipment to Novouralsk or Zelenogorsk.

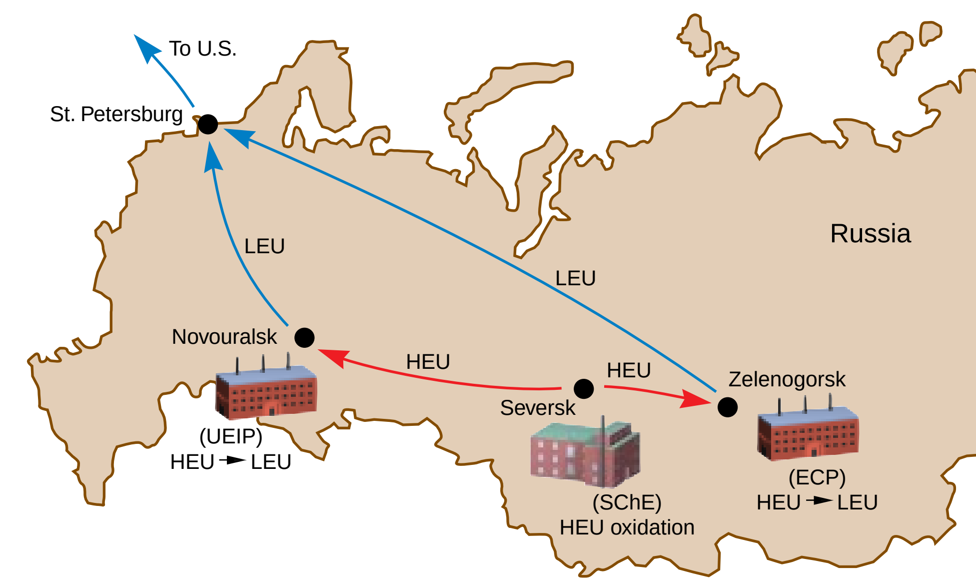


Figure 2. The U.S. is permitted to monitor highly enriched uranium (HEU) processing at the three locations shown. At the Siberian Chemical Enterprises (SChE) in Seversk, HEU metal is converted to HEU oxide and then shipped by train to the Ural Electrochemical Integrated Plant (UEIP) in Novouralsk or the Electrochemical Plant (ECP) in Zelenogorsk, where it is fluorinated and blended to produce low-enriched uranium (LEU). The LEU is shipped via St. Petersburg to the U.S., where it is made into commercial nuclear reactor fuel.

Figure 3. Principal investigators T. G. Nieh (left) and Donald Lesuer (center) join Bradley Tuvey of Lawrence Livermore's Procurement Department in examining samples of the automobile wheels made in Russia using a superplastic deformation technology previously used to make weapons components.

When the containers of oxide arrive at those sites, monitors first check the tags and seals on them. Then, says Leich, "We can request nondestructive assay of containers of HEU oxide, observe the feeding of oxide into a process that chemically converts the HEU to a hexafluoride form, and perform an assay of the HEU hexafluoride withdrawn from the conversion process. During the blending-down process, we can request random samples of the HEU hexafluorides, the blending materials, and the resulting LEU right out of the process piping and put them through an analysis procedure." U.S. and Russian monitors also have the right to measure the total flow of uranium at the blending point. Before the LEU is put on railcars to start its journey to the U.S., the monitors observe the application of Russian and U.S. tags and seals.

Monitoring at Seversk and Zelenogorsk is confined to periodic visits, but monitors have continuous access to the Novouralsk plant through the U.S. Permanent Presence Office there, which Lawrence Livermore manages for DOE. At all three plants, U.S. monitors have access to relevant documentation and accountability records.

Toward Peaceful Enterprises

Lawrence Livermore is currently active in several programs that provide collaborative project opportunities for scientists from the newly independent states, principally Russia, Ukraine, Belarus, and Kazakhstan. The goal of these programs is to direct the scientists toward work that will help develop free-market economies in their home states.

The first of these programs is the laboratory-to-laboratory program, which began in 1992 shortly after the directors of the Russian and American nuclear weapons design laboratories exchanged visits. Supported and monitored but not directly funded by DOE, the lab-to-lab program involves interactions between NIS institutes and DOE laboratories for the purpose of "encouraging exchanges of information between U.S. and NIS scientists, thereby building confidence and openness between the two sides," according to Janet Hauber, Group Leader for Cooperative R&D and facilitator of Livermore's laboratory-to-laboratory efforts. Funding for projects that result from these collaborations comes from the sponsoring DOE laboratory with the stipulation that the work is neither related to weapons development nor enhances weapons capability.

Hauber reviews the work between the NIS and U.S. scientists to assess the benefits derived by the participants. Although DOE is kept informed about lab-to-lab projects, the technical contacts are made directly by the scientists and involve only the laboratories and institutes. Thus, scientific collaborations are both informal and easy to initiate.

The laboratory-to-laboratory model for doing business has been so successful that it has been adopted by the Initiatives for Proliferation Prevention (IPP) program, another source of cooperative work for NIS scientists. Hauber is a member of the Interlaboratory Advisory Board of the IPP, her primary project responsibility. Sponsored and directly funded by DOE, the IPP program supports collaborations between NIS and DOE national laboratory scientists. The objectives of the IPP, like those of the lab-to-lab program, are to strengthen nonproliferation and keep NIS scientists employed in their current institutions, but unlike the lab-to-lab program, the focus of IPP-sponsored projects is clearly on their commercial potential.

Although projects must be mutually beneficial and not related to weapons, the major emphasis of IPP projects is on promoting economic recovery in the NIS. To that end, a large effort is expended on developing NIS know-how in the areas of intellectual property rights, entrepreneurship, and commercialization. To facilitate these collaborations, DOE has simplified the project review and approval process and promoted uniform administrative procedures, such as uniform contracts and general patents, which make it easier to protect intellectual property.

Projects done under the IPP program are carried out in three stages. In the first stage, the collaborating laboratories and institutes perform a feasibility study. Since the beginning of the program in 1994, some 200 projects in technical areas such as materials manufacturing, biotechnology, energy, and waste management have been initiated. Projects considered to be feasible move into a second stage, one in which private industry can participate through cost-sharing (by matching government funding) and by assisting in prototype development. A number of projects are currently in this second stage.

A typical project—an analysis of the use of superplastic deformation technology to make automobile wheels—is being performed by a consortium made up of Lawrence Livermore, the All Russian Institute of Technical Physics, the (Russian) Institute of Metals Superplasticity Problems, Kaiser Aluminum, and Rockwell International. Lawrence Livermore's specific role at this juncture is to characterize wheel design and material for compliance with U.S. Department of Transportation standards and to determine whether the wheel will be able to meet U.S. requirements (Figure 3). Once the superplastic technology has been fully developed, it has potentially many more uses than for making car wheels. Because it uses nearly all of its starting materials to form the final product, it is a beneficial technology that produces few industrial waste byproducts. Also, because it is a technology previously used to make weapons components, it will be a true swords-to-plowshares project.

The third stage of IPP projects involves production of the developed products in the context of a purely commercial agreement between the Russian entity and a U.S. industrial firm.

While the progress of IPP projects is sometimes slow, Hauber is enthusiastic about the program, believing that it will be an important factor in developing strong economies for the NIS. She says that "we just need to continue this work a little longer. The Russians are determined, and that determination will go a long way toward a successful outcome."

International Support

A third program provides project opportunities to NIS scientists through the International Science and Technology Center (ISTC) in Moscow and the Science and Technology Center of the Ukraine in Kiev. Established by agreements among participating governments, the centers develop and fund nonproliferation projects whose primary objective is to provide peaceful, non-weapons-related opportunities to weapons scientists and engineers from the NIS, particularly those with knowledge and skill in the development of weapons of mass destruction (nuclear, chemical, and biological).

Although headquartered in Moscow, the ISTC is available to other states of the former Soviet Union—so far, scientists from Russia, Armenia, Belarus, Georgia, Kazakstan, and Kirgizia have submitted proposals. The ISTC is supported by the U.S., the European Union (EU),* Norway, and Japan. The EU, Japan, and U.S. each place a deputy director at the Center and provide staff support for Center operations such as finance and program management. The parties rotate the Center directorship as well as the chair of its governing board. The current chairperson of the governing board is Ron Lehman, Director of the Center for Global Security Research at Lawrence Livermore.

The ISTC sponsors projects focused on developing scientific and technical solutions for national and international problems, reinforcing the transition to a market economy, developing basic science and technology, and promoting the further integration of NIS scientists into the international scientific community. Project proposals submitted to the ISTC are evaluated for scientific

* The member nations of the European Union are: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

MINATOM
Civilian Complex

1. Dmitrovgrad, Scientific Research Institute of Atomic Reactors (NIIAR)
2. Elektrostal Production Association Machine Building Plant (POMZ)
3. Obninsk, Physics & Power Engineering Institute (FEI)
4. Podolsk, Scientific Production Association Luch
5. Novosibirsk Chemical Concentrates Plant
6. Beloyarsk Nuclear Power Plant
7. Sverdlovsk Branch of Scientific Research and Design Institute of Power Technology (NIKIET)
8. Scientific Research and Design Institute of Power Technology (NIKIET)
9. Khlopin Radium Institute
10. Moscow Institute of Theoretical and Experimental Physics
11. St. Petersburg Central Design Bureau of Machine Building

MINATOM
Defense Complex

12. Arzamas-16/Sarov, All-Russian Scientific Research Institute of Experimental Physics (VNIIEF)
13. Krasnoyarsk-26/*Zheleznogorsk**, Mining and Chemical Combine
14. Krasnoyarsk-45/*Zelenogorsk*, Electrochemical Plant
15. Chelyabinsk-65/*Ozersk*, Mayak Production Association
16. Chelyabinsk-70/*Snezhinsk*, All-Russian Scientific Research Institute of Technical Physics (VNIITF)
17. Sverdlovsk-44/*Novouralsk*, Urals Electrochemical Integrated Plant
18. Tomsk-7/*Seversk*, Siberian Chemical Combine
19. ELERON (Special Scientific and Production State Establishment)
20. All-Russian Scientific Research Institute of Automatics (VNIIA)
21. Bochvar All-Russian Scientific Research Institute of Inorganic Materials (VNIINM)

*Italics indicate new Russian place names.

Independent
Civilian Sector

22. Russian Scientific Research Center– Kurchatov Institute
23. Karpov Institute of Physical Chemistry, Obninsk
24. Tomsk, Scientific Research Institute of Nuclear Physics
25. Norilsk, Nikel Plant
26. St. Petersburg Institute of Nuclear Physics
27. Joint Institute of Nuclear Research, Dubna
28. Moscow Institute of Physical Engineering (MIFI)

Naval Nuclear
Fuel Sector

29. Northern Fleet
30. Pacific Fleet
31. Icebreaker Fleet (Murmansk Shipping Company)

Non-Russian NIS
and Baltic Sector

32. Sosny Institute of Nuclear Power Engineering, Minsk, Belarus
33. Tbilisi, Institute of Physics, Georgia
34. Aktau, BN-350 Breeder Reactor, Kazakstan
35. Almaty, Research Reactor, Kazakstan
36. Semipalatinsk, Complex 21, Kazakstan
37. Ulba Fuel Fabrication Plant, Ust'Kamenogorsk, Kazakstan
38. Salispals Institute of Nuclear Physics, Latvia
39. Ignalina Nuclear Power Plant (INPP), Lithuania
40. Kharkiv Institute for Physics and Technology (KIPT), Ukraine
41. Kiev Institute of Nuclear Research (KINR), Ukraine
42. Sevastopol Naval Institute, Ukraine
43. South Ukraine Nuclear Power Plant (SUNPP), Konstantinovsk, Ukraine
44. Tashkent, Institute of Nuclear Physics, Uzbekistan

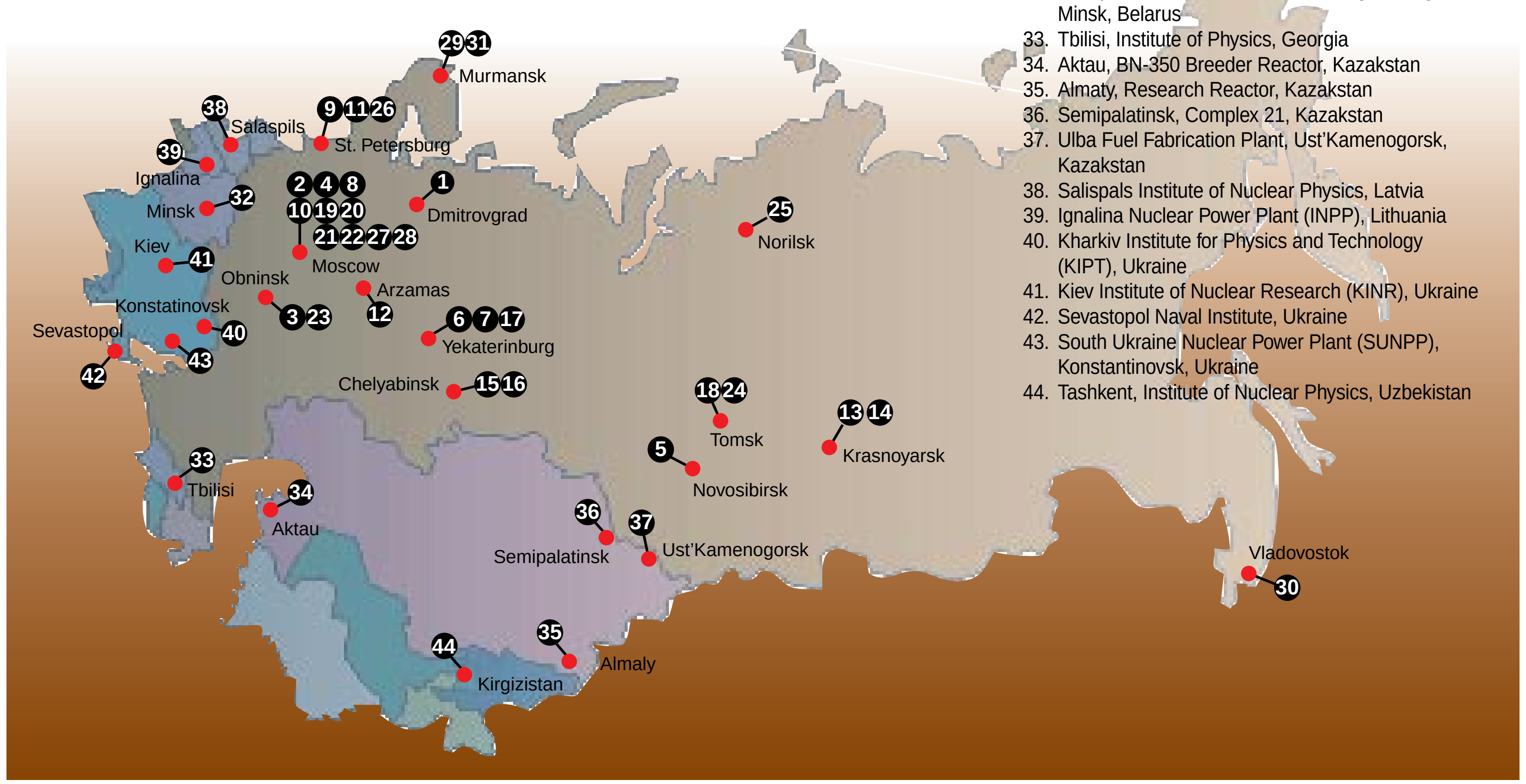


Figure 4. The DOE Materials Protection, Control, and Accounting program currently has projects to improve security and material accountability at 44 sites in the newly independent states where nuclear materials are processed and stored. One of several projects with which Livermore currently is involved is at Chelyabinsk-70 (Snezhinsk), number 16 on the map.

merit by the funding parties. Eileen Vergino, Lawrence Livermore's Program Manager for the ISTC, sits on the U.S. scientific advisory committee and provides technical support to the U.S. State Department, both by finding scientific reviewers for submitted technical proposals and advising them on funding decisions. Proposals are evaluated for technical merit as well as for conformance to ISTC policy. Overall approval is provided by the ISTC governing board, and final funding decisions are made by the funding party.

U.S. scientists, including those at DOE laboratories, are encouraged to express support for or, better yet, collaborate on proposals they find interesting and significant to their area of expertise. A firm commitment by U.S. collaborators to a project will improve its chances for funding. While the U.S. collaborators will not receive any funding, they will play a key role in project development and review. U.S. collaborators often see the ISTC as a means for leveraging funds and enabling collaborations between themselves and NIS scientists on projects ranging from reactor safety to treaty verification to environmental assessment and cleanup.

The Science and Technology Center of Ukraine is modeled after the ISTC. Its main difference is its sponsors, currently composed of the U.S., Canada, and Sweden and soon to include the EU and Japan.

Security and Accountability

Russia's transition toward democracy has changed its state mechanisms for controlling and securing nuclear materials. Because of the economic and social changes in Russia, the borders around weapons complexes are now more permeable; gaining access to weapons materials has become easier. These factors increase the potential for the theft of nuclear materials. Therefore, one of the larger U.S. efforts in Russia is to provide assistance for improving the physical protection, control, and accounting of Russia's nuclear materials.

The DOE Materials Protection, Control, and Accounting (MPC&A) program is a cooperative effort with Russian institutes and enterprises that process or store nuclear materials usable in weapons. Lawrence Livermore is one of seven DOE national laboratories involved in the program and is working directly with Russia's nuclear institutes to provide them with technical support, training, funding, and equipment. The goal is twofold: enhance Russian physical protection and nuclear material accounting capabilities and encourage an overall change of philosophy about physical and material protection. The program is intended to foster support from institutes and scientists for enhanced security concepts and methodologies that will be the foundation for enhanced national standards throughout the newly independent states.

Begun in 1994 with pilot projects at three Russian institutes and modeled, like the IPP program, after the laboratory-to-laboratory program discussed earlier, the MPC&A program has expanded to more than 44 institutes and enterprises (Figure 4). One or more project teams have formed at each institute or enterprise. One of the several project teams led by Lawrence Livermore has responsibility for Chelyabinsk-70.

T. R. Koncher, leader of Lawrence Livermore's MPC&A work, says, "We think of Chelyabinsk-70 as Russia's equivalent to Lawrence Livermore because it is their second oldest weapons complex, just as we think of Arzamas-16 as their Los Alamos." Chelyabinsk-70, now called Snezhinsk, is east of the Ural Mountains, approximately 1,900 kilometers east of Moscow and about 80 kilometers south of Ekaterinburg. Several other nuclear facilities located nearby have close relationships with it, so it is expected that any security improvement techniques developed at Chelyabinsk-70 will ultimately be beneficial to these other institutes as well.

Security Upgrades

Lawrence Livermore's approach to upgrading safeguards and security at Russian weapons complexes is to work with Russian colleagues to identify areas where upgrades are required and then rapidly install those upgrades. The MPC&A program first installed safeguards such as barriers, alarms, communications systems, and portal monitoring systems. Subsequently, pedestrian and vehicle portals were installed to improve entry and exit systems (Figure 5). Older Russian manual systems are being replaced with automated control systems that will incorporate nuclear material monitors, metal detectors, and ballistically hardened booths for the guards. The new systems can detect nuclear materials being smuggled out, improve the capability to discover anyone trying to sneak inside, and offer better protection for guards in the event of an attack.

Lawrence Livermore is also working to enhance Russian transportation systems for nuclear materials. The Automatic Transportation Security System (ATSS) is an ongoing project to use readily available technologies to make rail systems more secure. The three-phase project, scheduled to be completed in the year 2000, covers some 375 development tasks. The first phase, now under way, includes installing intrusion and environmental sensors, security seals, on-train data communications and display, voice communications, physical barriers, locks, active delays such as high-intensity explosive sound generators and smoke generators, and off-train data

Figure 5. With the help of Livermore and other DOE laboratories, the Materials Protection, Control, and Accounting program has upgraded the safeguards and security at Russian weapons complexes. Shown here are (right) a pedestrian portal monitor and (below) a drive-through vehicle portal monitor.

communications and tracking. In parallel to the physical controls, U.S. and Russian scientists are developing safety methodologies—for example, procedures for coordinating emergency response from a central command post.

Improvements for the ATSS were designed at Moscow's Eleron Institute, which is devoted to the development, manufacture, and implementation of security equipment and systems. Actual implementation of the improvements will be done in conjunction with seven other Russian institutions, which will assure that the system has been incorporated into the Russian transportation infrastructure.

Efforts are also under way to obtain an accurate measure of nuclear material inventories and to establish procedures for checking and evaluating material balances regularly throughout all operations. This work requires the use of nondestructive assay methods to measure or verify nuclear inventories efficiently. U.S. scientists, for instance, are providing a gamma-ray spectrometer that can measure plutonium isotopes or uranium enrichment and thus determine and verify nuclear inventories (Figure 6). Lawrence Livermore scientists developed the codes required to interpret the gamma-ray measurements. The codes analyze the complex gamma-ray spectra of plutonium or uranium to determine the actinide isotopic distribution for samples of any physical form, size, shape, or chemical formula. The system is easy to use: it does not require calibration of the instrumentation, and its measurement and analysis times are short.

Long-Term Assessments

In addition to upgrading security weaknesses, U.S. scientists are helping Russian scientists assess long-term security infrastructure needs and establish priorities for implementation. Lawrence Livermore, in conjunction with Sandia National Laboratories, has been working with Russian institutes to conduct vulnerability analyses. This work, which generally begins with a training workshop, teaches quantitative probabilistic risk analysis, the technique that DOE uses to evaluate protection systems for special nuclear materials. The focus of these workshops is on using a computer-based analysis tool called ASSESS (Analytical System and Software for Evaluating Safeguards and Security) to quantify the detection, delay, and neutralization probabilities of various protection systems. The quantitative values depend on the objectives of the protection system. These objectives, in turn, are defined through an analysis that asks: What needs protection? What are the consequences of losing the material? What possible types of threat does it face? What is the maximum level of acceptable risk for it? The objectives of the protection system must be identified and understood before an evaluation can be made of its effectiveness.

In addition to the workshops, subsequent vulnerability analyses, performed solely by Russians or jointly with U.S. scientists, are used to evaluate and prioritize physical and procedural security upgrades. The approach of these analyses differs from the present Russian approaches, so the rationale of the analysis tools must be communicated. The work also has to do with inculcating an MPC&A culture throughout the Russian institutes, so that both physical protection to fight off outsider threats and resistance to insider threats will be improved.

Additional Benefits

Lawrence Livermore's work in the area of nonproliferation and arms control is one of critical importance to national and global security. This work draws on the expertise of personnel from directorates throughout Lawrence Livermore: Nonproliferation, Arms Control, and International Security as well as Engineering, Physics and Space Technology, Environmental Programs, Energy Programs, Chemistry and Materials Science, Computation, and Plant Operations. These staff are involved in the nonproliferation effort because their technical expertise allows them to work directly with scientists from Russia and other newly independent states in ways that diplomats and politicians could not. Their face-to-face interactions are yielding benefits beyond the goals of their various collaborative efforts. As Bill Dunlop, Program Leader, Proliferation Prevention and Arms Control, notes, "The access that U.S. and Russian scientists now have to each other's secure facilities is remarkable. It would have been unimaginable not too long ago. This level of trust results from common technical expertise, our similar background in national security issues, and our mutual respect."

—Gloria Wilt

Key Words: arms reduction; Chelyabinsk-70; gamma-ray spectrometer; highly enriched uranium (HEU); Initiatives for Proliferation Prevention (IPP); International Science and Technology Center (ISTC); laboratory-to-laboratory program; low-enriched uranium (LEU); Materials Protection, Control, and Accounting (MPC&A) program; newly independent states (NIS); nuclear nonproliferation; Nunn–Lugar Cooperative Threat Reduction bill; safeguards, transparency, and irreversibility; transparency measures; verification; vulnerability analysis; Russia.

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Figure 6. This prototype gamma-ray spectrometer can quickly, easily, and nondestructively determine the isotopic signatures of plutonium and enriched uranium using computer codes developed at Livermore.

About the Team

Lawrence Livermore personnel who contributed to this article are: (back row, left to right) PAUL HERMAN, JIM MORGAN, and SCOTT MCALLISTER; (front row) BILL DUNLOP, EILEEN VERGINO, and DOUG LEICH. (Not pictured are T. R. KONCHER, DEBBIE BALL, and JANET HAUBER.) All, except Leich, are members of the Proliferation Prevention and Arms Control Program, which is part of the Nonproliferation, Arms Control, and International Security Directorate. Leich is part of the Fusion Energy and Systems Safety Program in the Energy Directorate.

The work of these scientists and engineers is performed under the auspices of the U.S. Departments of Energy and State and focuses on reducing the risks of nuclear proliferation through collaboration and partnership with scientists and engineers in the newly independent states of the former Soviet Union. Projects range from negotiating mutually acceptable ways to monitor arms reduction and the disposition of excess nuclear materials to developing technologies to safeguard nuclear materials from theft or diversion to promoting commercial, non-weapons applications of nuclear weapons know-how and technology.

Taming Explosives for Training

IT looks like a bomb. It even smells like a bomb—enough to fool man's best friend, the pooch who's trained to sniff out explosives. But it won't explode and won't even burn decently.

So who wants a dud like that? Not your average terrorist. But the bogus bombs fabricated of nonhazardous explosives for security training and testing (NESTT) by Lawrence Livermore are piquing the interest of scores of organizations responsible for calibrating explosive-detection machines and for training humans and dogs in detecting explosive devices. In fact, Lawrence Livermore is close to completing a commercial licensing agreement for NESTT.

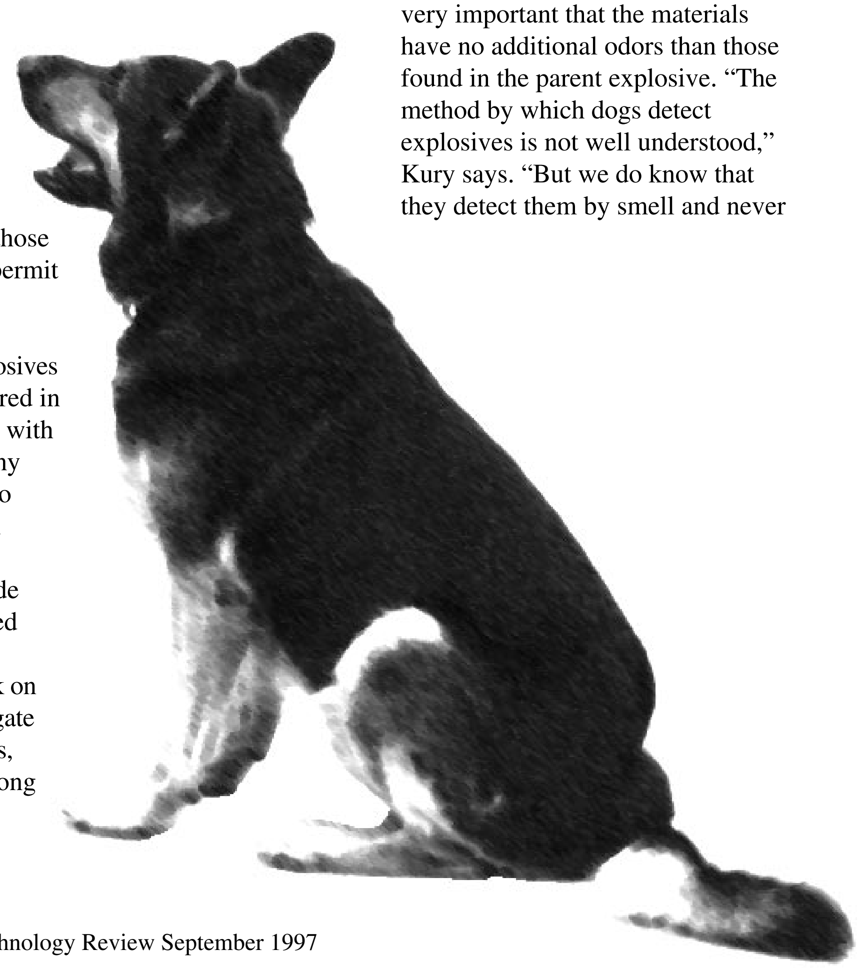
"We started the NESTT project about seven years ago," says John Kury, the explosives chemist who heads the project. "We had a fairly narrow need to provide a safe alternative to using actual explosives in training Livermore's canine explosives-detection teams, which have since been disbanded. As word got around about the project, we discovered a much broader need throughout the country."

When the Laboratory was training its own canine teams at the beginning of the decade, the teams had to use actual explosives and deal with the inherent dangers. Almost all the training had to take place at Site 300, the Lab's explosive test facility, where conditions certainly do not resemble those in an office building or airport. A safe substitute would permit training with a larger amount of material under far more realistic simulations.

But safety and realism aren't the only issues. Live explosives demand extra expense and care because they must be stored in bunkers or specially designed magazines and transported with special precautions. NESTT can be transported without any special precautions other than extensive documentation to prove that it is not what dogs and detection machines tell guards and police it is.

The simulated explosives made by Kury's team include stand-ins for TNT and a standard military explosive called Composition C-4 (Comp C-4), which contains RDX. By coating a layer of explosive that is a few micrometers thick on a nonreactive substance, Kury and his team produce surrogate materials that have many authentic properties of explosives, including vapor and molecular signatures. However, as long as the concentration of the parent explosive (TNT or RDX) is under approximately 8%, the materials remain nonhazardous. Kury says an early test was conducted in the Laboratory Director's conference room with about a pound of the simulated explosive—enough, if it were real, to completely destroy the room. "The dog hit it immediately," Kury says. "An animal acts differently in different environments. If you can train in real environments, there is a much better probability of a successful find."

In fact, preliminary results were so successful that larger quantities were prepared for a beta test program, which included U.S. and foreign canine units and companies that manufacture explosive-detection instruments.



Getting the Formulation Right

For the canine program, it was very important that the materials have no additional odors than those found in the parent explosive. "The method by which dogs detect explosives is not well understood," Kury says. "But we do know that they detect them by smell and never confuse glass with explosives. So it's important that the 'odor signature' of the parent explosive is maintained, and odorless silica was a natural choice for the substrate."

Kury and the team devised a formulation for dog training that uses 92% (by weight) fused silica of high purity as the substrate, onto which 8% TNT is deposited—rather like coating candy with an extremely thin layer of sugar. The formulation for the simulated Comp C-4 includes 8% RDX and 76.5% silica, along with the C-4 binder system (9.2% dioctal adipate, 2.7% polyisobutylene, and 3.6% oil).

The NESTT formulation for instrument testing is prepared by dissolving 3.3% polyisobutylene, 8.3% dioctal adipate, and 2.5% oil in pentane. That solution, along with 7.4% RDX and 78.5% cyanuric acid, is put in a high-shear mixer. The pentane is removed during mixing, and the resultant putty material is dried in an oven and molded into 2.5- by 5.0- by 30.5-centimeter bars, nearly identical to the Comp C-4 demolition bars produced by the U.S. Army. This formulation duplicates the oxygen–nitrogen ratio, effective atomic number, and density of the real explosive.

The materials have been tested in both small-scale laboratory tests and large-scale sensitivity tests, and they did not react in either the shock-sensitivity or flammability tests. Similar results were obtained by the Department of Defense when it tested mixtures of 15% or less of TNT or RDX mixed with sand.

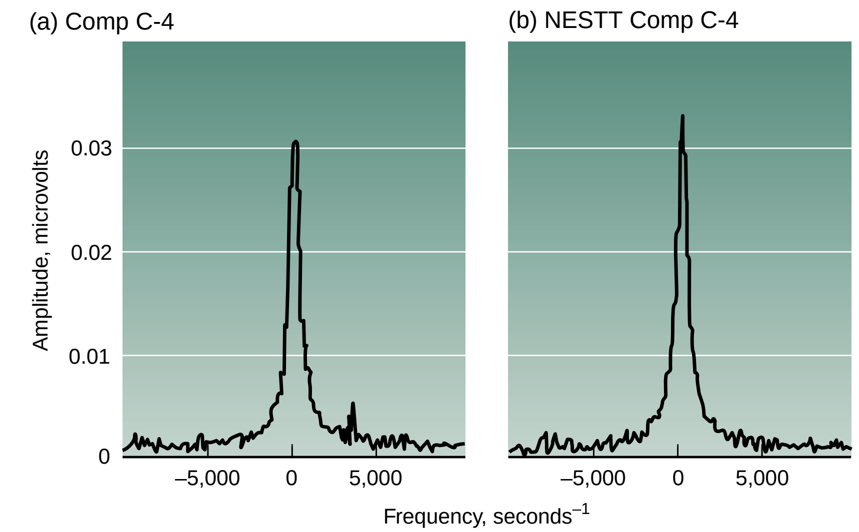


Figure 1. Nuclear quadrupole resonance spectra for (a) the explosive Comp C-4 and (b) NESTT Comp C-4 indicate that the NESTT formulation can be used to calibrate detection machines.

Proof Is in the Tests

The NESTT canine test samples are formulated and packaged carefully to ensure that their odor signatures are identical to those of the parent explosives. Fused silica is also used as the packing material for shipping the samples to minimize the possibility of contamination by other organic compounds. To check the odor signature, Kury and the team use mass spectrometer analyses to verify that the vapor collected from TNT is identical to that from the NESTT TNT.

The test program has involved more than 200 handler–canine teams from U.S. and foreign agencies. More than 95% of the teams report that the canines react to the NESTT materials in the same manner they do to the parent explosive. And the 5% that did not react to the NESTT materials as they do to the parent explosive likely did so for reasons other than the authenticity of the NESTT explosive signature—e.g., the dogs were trained on "non-pure" parent explosive.

Several agencies have used only NESTT materials to train a few new canines. In all of these cases, the canines are able to detect samples of the parent explosives, TNT and C-4, reliably. These results, coupled with vapor analysis, verify that NESTT materials have authentic odor signatures.

While old Fido's nose can't be understood with scientific precision, the results of detection instruments can. So Kury's team sent samples to various organizations to see how the simulated explosives stack up against the real thing. Using nuclear quadrupole resonance, Quantum Magnetics of San Diego, California, found that the resonance of the nitrogen-14 isotope at 3.41 megahertz for RDX in NESTT was identical to that for RDX in Comp C-4, clearly indicating that the NESTT material can be used to calibrate detection machines (Figure 1).

Both TNT and RDX NESTT materials were tested by Thermedics Detection Inc. using its EGIS detection system, in which vapor and particulate samples are collected and the explosives are identified by analysis of selected decomposition products. The system detected the presence of explosive not only in the NESTT sample itself, but also on the courier's hands and the briefcase that was used to transport the sample (Figure 2). The following day, a canine being trained by the

Connecticut State Police also reacted positively to the then-empty but still-contaminated briefcase.

NESTT Comp C-4 was tested on x-ray explosive-detection equipment made by Invision Technologies Inc. and VIVID Technologies Inc. Both tests gave positive results, indicating that NESTT has the same effective atomic number and density as a real explosive sample.

The beta test program demonstrated that the nonhazardous NESTT materials can benefit explosive-detection programs throughout the world. Few companies or agencies have the ability to use and store realistic quantities of explosives. With NESTT, realistic sites and scenarios can be used safely and economically to train canines that sniff out explosives and personnel who operate detection equipment.

—Sam Hunter

Key Words: canine training, nonhazardous explosives for security training and testing (NESTT), simulated explosives.

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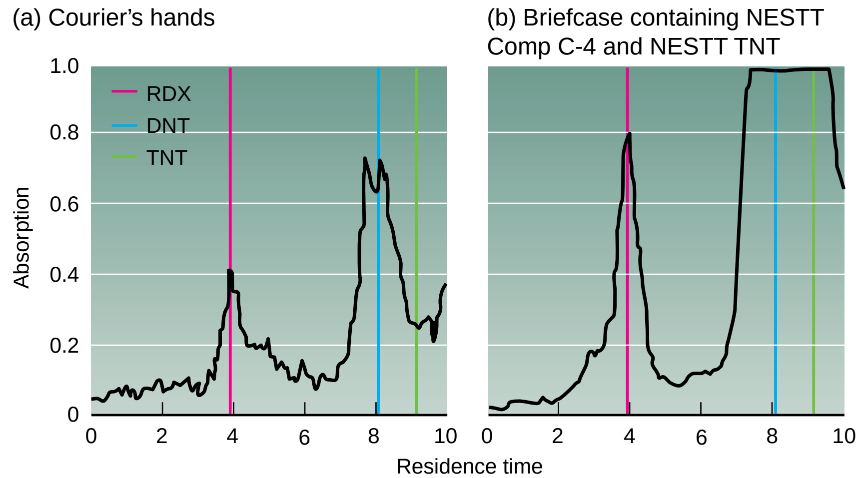

Figure 2. Chromatographic analysis (in arbitrary units) of the samples indicate the presence of RDX and TNT not only in the NESTT samples, but also (a) on the hands of the courier and (b) on the briefcase used to transport the NESTT materials.

Patents

Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
John C. Whitehead Joe N. Lucas	**Fluid Driven Reciprocating Apparatus** U.S. Patent 5,616,005 April 1, 1997	A pair of fluid-driven pump assemblies in a back-to-back configuration to yield a bi-directional pump. Each pump assembly includes a piston or diaphragm that divides a chamber into a power section and a pumping section. An intake–exhaust valve connected to each power section functions to direct fluid, such as compressed air, into the power section and to exhaust fluid. At least one of the pistons or diaphragms is connected by a rod assembly, which is constructed to form a signal valve. The intake–exhaust valve of one pump assembly is controlled by the position or location of the piston or diaphragm in the other pump assembly through the operation of the rod assembly signal valve.
Joe N. Lucas Tore Straume Kenneth T. Bogen	**Detection and Isolation of Nucleic Acid Sequences Using Competitive Hybridization Probes** U.S. Patent 5,616,465 April 1, 1997	A method in which a target nucleic acid sequence is hybridized to first and second hybridization probes that are complementary to overlapping portions of the target nucleic acid sequence. The first hybridization probe includes a first complexing agent capable of forming a binding pair with a second complexing agent, and the second hybridization probe includes a detectable marker. The first complexing agent attached to the first hybridization probe is contacted with a second complexing agent, which is attached to a solid support such that when the first and second complexing agents are attached, target nucleic acid sequences hybridized to the first hybridization probe become immobilized onto the solid support. The immobilized target nucleic acids are then separated and detected by the identification of the detectable marker attached to the second hybridization probe.
Raymond J. Beach William J. Benett Steven T. Mills	**Fiber Optic Coupling of a Microlens Conditioned, Stacked Semiconductor Laser Diode Array** U.S. Patent 5,617,492 April 1, 1997	A system for efficiently coupling the output radiation from a two-dimensional aperture of a semiconductor laser diode array into an optical fiber. The aperture is formed by stacking laser diode bars. Individual microlenses condition the output radiation of the laser diode bars for coupling into the fiber. A simple lens is then used to focus this conditioned radiation into the fiber. The focal length of the lens is chosen such that the divergence of the laser light after it passes through the lens is not greater than the numerical aperture of the optical fiber. The lens must focus the laser light to a spot size that is less than or equal to the input aperture of the optical fiber.
John F. Holzrichter Wigbert J. Siekhaus	**Method for Identifying Biochemical and Chemical Reactions and Micromechanical Processes Using Nanomechanical and Electronic Signal Identification** U.S. Patent 5,620,854 April 15, 1997	A method of operating a scanning probe microscope, such as an atomic force microscope (AFM) or a scanning tunneling microscope (STM), in a stationary mode on a site where an activity of interest occurs to measure and identify characteristic time-varying micromotions caused by biological, chemical, mechanical, electrical, optical, or physical processes. The tip and cantilever assembly of an AFM is used as a micromechanical detector of characteristic micromotions transmitted either directly by a site of interest or indirectly through the surrounding medium. Alternatively, the exponential dependence of the tunneling current on the size of the gap in an STM is used to detect micromechanical movement.
Charles E. Hamilton Laurence H. Furu	**Tunable, Diode Side-Pumped Er:YAG Laser** U.S. Patent 5,623,510 April 22, 1997	A discrete-element Er:YAG (erbium-doped yttrium–aluminum–garnet) laser side-pumped by a laser diode array which generates a tunable output around 2.94 micrometers. The oscillator is a plano-concave resonator consisting of a concave high reflector, a flat output coupler, an Er:YAG crystal, and an intracavity etalon tuning element. The oscillator uses total internal reflection in the Er:YAG crystal to allow efficient coupling of the diode emission into the resonating modes of the oscillator. The laser is useful for tuning to an atmospheric window, as a spectroscopic tool, for medical applications, and for industrial effluent monitoring.

(continued from page 2)

• **Multiscale Electrodynamics (MELD)**, by a team headed by Richard Ratowsky from the Physics and Space Technology Directorate. This simulation software is a breakthrough design tool with the potential to revolutionize the design process for opto-electronic devices and packages. MELD can model widely disparate elements, such as semiconductor waveguides, fibers, and lenses, using exactly the right method for each and providing a seamless interface between the elements—all accessed intuitively by a human operator. By reducing fabrication cycles, optimization time, and cost, the software offers the potential to increase the U.S. market share in today's $15-billion annual opto-electronic component market.
Contact: Richard Ratowsky (510) 423-3907 (ratowsky1@llnl.gov).

• **Oil Field Tiltmeter**, by a team headed by Steven Hunter from the Energy Programs Directorate. This instrument measures minute changes in tilt on two orthogonal axes. An array of these instruments is used to monitor oil well hydrofracture—a technique of cracking rock in an oil field to increase production—and provides valuable information for choosing optimal sites for oil wells. Previous technology could monitor hydrofractures only 6,000 feet deep, but this instrument is capable of monitoring in very expensive wells at least 10,000 feet deep.
Contact: Steven Hunter (510) 423-2219 (hunter5@llnl.gov).

• **Ultrahigh Gradient Insulator**, by a team, headed by Steve Sampayan, whose members come from the Defense and Nuclear Technologies and the Laser Programs directorates. This breakthrough in insulator technology improves the voltage breakdown performance of insulators up to a factor of four, thus opening up possibilities for reducing the size of all high-voltage equipment and developing new types of accelerators that were not possible previously. The new technology should revolutionize linear accelerators and reduce the size and cost of x-ray machines, neutron sources, and plasma radiation sources.
Contact: Ted Wieskamp (510) 422-8612 (wieskamp1@llnl.gov).

• **High-Performance Storage Systems**, by Oak Ridge National Laboratory working with Lawrence Livermore, Los Alamos, Sandia, and IBM Global Government Industry as participating institutions; Richard Watson of the Computation Directorate is Livermore's primary contact. This new storage system will enable users to store a quintillion bytes (an exabyte), which is more than ten thousand times the capability of today's supercomputing storage systems, to meet the needs of the Department of Energy's Accelerated Strategic Computing Initiative and Stockpile Stewardship and Management Program. New software allows huge capacities and transfer rates by using a network-centered design. Distributing the storage software system and storage devices over a network allows control of the system to be separated from the flow of data. These capabilities allow more rapid data transmission and scalability of performance and capacity, thus removing a bottleneck in data storage, transfer, and retrieval.
Contact: Richard Watson (510) 422-9216 (watson9@llnl.gov).

Abstracts

Nova Laser Experiments and Stockpile Stewardship

High-power lasers contribute to the experimental study of matter under conditions of extremely high energy density, the conditions that exist in the interior of stars and in nuclear explosions. Experiments on the Nova laser system have helped resolve questions in three important areas of basic physics: equations of state, hydrodynamic instabilities, and opacity. The results of these experiments suggest that high-power lasers can play a significant role in a comprehensive, laboratory-based experimental program to support the Department of Energy's Stockpile Stewardship and Management Program.
■ *Contact:*
Ted Perry (510) 423-2065 (tedperry@llnl.gov) or
Bruce Remington (510) 423-2712 (remington2@llnl.gov).

Sharing the Challenges of Nonproliferation

Lawrence Livermore scientists have been traveling to Russia and other newly independent states of the former Soviet Union to negotiate and collaborate with their counterparts in efforts to promote global nuclear security. Under the auspices of Nunn–Lugar legislation and the nonproliferation initiatives of the Departments of Energy and State, Lawrence Livermore scientists and engineers have helped negotiate transparency measures to confirm the progress of arms reduction activities, monitored Russian processing of weapons materials for conversion to civilian energy production, worked with and guided scientists from the newly independent states toward non-weapons projects, and worked with Russian weapons scientists to upgrade security and fissile material accountability of fissile material stored or processed at Russian nuclear facilities.
■ *Contact:*
William Dunlop (510) 422-9390 (dunlop1@llnl.gov).

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