

“Shocking” Gas-Gun Experiments

Livermore’s big gas gun creates shock waves that are millions of times atmospheric pressure at Earth’s surface.

TAKE a small car cruising down the highway at 90 kilometers per hour and put its kinetic energy into something the size of an ice cube. That’s the energy of the small projectile screaming down the barrel of Livermore’s gas gun at 8 kilometers per second—three quarters of the velocity needed to escape Earth’s gravity. When the projectile hits its target, the pressure of the resulting shock wave is over 600 gigapascals, 6 million times the pressure of air at Earth’s surface. You don’t want to be on the receiving end of that.

These extraordinarily high pressures, created experimentally by the gas gun, occur during explosions, the detonation of nuclear weapons, in inertial fusion experiments, or when a large meteorite hits Earth. These pressures are also a way of life at the core of our own planet and inside the giant planets of our solar system. The high pressures of a shock wave make materials denser and heat them to thousands of degrees.

Livermore’s early shock physics experiments were designed so that scientists could learn what happens to gases, fluids, and solids when they are exposed to shock waves. In the days when Livermore was designing new weapons, better data about materials at high pressures led to improved output

from weapon design codes and simulation models so that they better replicated the results of experiments.

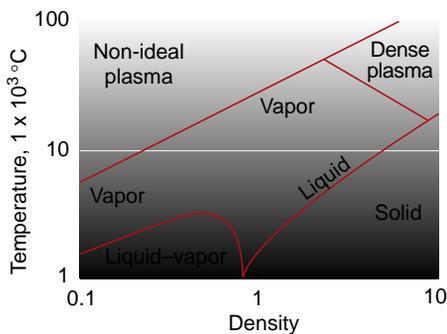
Today, the Department of Energy’s science-based Stockpile Stewardship Program demands that researchers be able not just to match the results of experiments but actually to predict in

detail the behavior of stockpiled nuclear weapons. This mission puts a premium on understanding the basic underlying science. Knowing the properties of weapon materials is critical to understanding every weapon component and its ongoing performance. Yet even after several decades of working with,

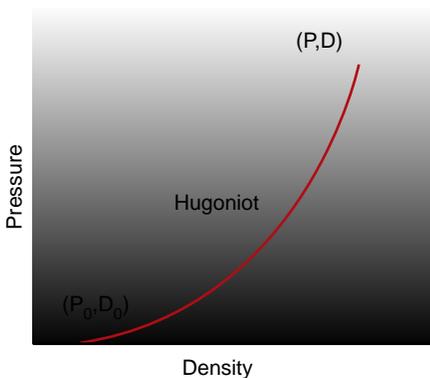


Livermore’s largest two-stage gas gun is 20 meters long. Its projectile flies down the barrel at speeds up to 8 kilometers per second to produce a shock wave millions of times the pressure of air at the surface of Earth. Technicians Leon Raper (left) and Keith Stickle are setting up the gas gun for an experiment.

say, the byproducts of high explosives, weapons scientists are still missing much information. The byproducts are disarmingly simple—water, carbon dioxide, and nitrogen. But at high pressures, densities, and temperatures, their behavior is often anything but simple. Experiments that reveal their fundamental nature are essential to predicting their behavior and, by extension, the performance of the overall weapon.



A phase diagram for a hypothetical material shows how the material changes as temperature and density (a function of pressure) change.



This is the Hugoniot curve for a hypothetical target material. The pressure (P) and density (D) of a target before impact are P_0 and D_0 . When the target is hit and compressed, its pressure and density increase to P and D . A series of compression experiments of varying shock strengths will result in the curve shown.

Livermore is one of just a few institutions in the world with a major shock physics experimental program. Notes physicist Neil Holmes, who leads the shock physics program at Livermore, “Each of the three DOE weapons laboratories has its areas of expertise, and the physics of shocked fluids and condensed matter is one of ours.

Although gas-gun experiments have been under way since the early 1970s, there is still so much we need to learn.”

He goes on to say, “What started as strictly weapons research has broadened considerably. Experiments about the properties of iron under shock conditions tell us about the center of our own planet where iron exists under high pressures and temperatures. We have also applied data about hydrogen and other molecular fluids such as water to understanding the giant planets in our solar system. For example, the interiors of Uranus and Neptune are made up mostly of complex molecular fluid under high pressures and temperatures. The molecules that make up the fluid are the same molecules as those of the detonation products of high explosives. Our experiments are like sending a probe deep inside those planets.”

Under shock conditions, it is also possible to induce novel configurations that give materials entirely new properties. It was theorized in 1935 that under extremely high pressures, hydrogen would become a metal at room temperature. The effort continues today to find the predicted solid metallic hydrogen. In 1994, however, a team of Livermore researchers produced fluid metallic hydrogen using shock compression. Suddenly, fluid hydrogen was a conductor rather than an insulator (*S&TR*, September 1996, pp. 12–18).

Still other experiments at Livermore are using lasers and pulsed power to induce even higher pressures than the gas gun can achieve. And then there is the diamond anvil cell, which exerts high pressures but not shock waves. The

diamond anvil cell operates slowly, allowing careful observation over many hours or days of how a material responds to pressure. This is in contrast to the gas gun, whose shock experiments are over in a millionth of a second or less. (See the box on p. 15 for information on how the gas gun works.)

Measuring Change

All materials change phase if pressure and temperature change enough. We all know about water, which is in the gas phase—steam—at high temperature and in the solid phase—ice—at low temperature. What may be less well known is that as pressures increase, different kinds of ice form. All materials have a phase diagram that shows how its phases change as pressure and temperature change, as shown in the top figure to the left.

A shock wave can change the phase of a material, vaporizing a solid, for example. When a shock wave hits a target, it travels in the target material with a supersonic velocity, taking it to a new state with higher density, temperature, and pressure.

The shock wave is used to find the relationship between the target’s pressure, density, and temperature, which together constitute the material’s equation of state. Experiments to determine the equation of state of various materials have formed the basis of Livermore’s shock physics program for years, and these data are input into weapon simulations.

In shock physics experiments, a curve known as the Hugoniot is a valuable tool for analyzing a material’s equation of state. If a material with a defined initial pressure, density, and energy is subjected to a series of compression experiments of varying shock strengths, a set of new compression states can be plotted. The resulting curve is the material’s Hugoniot. Every material has a unique

Hugoniot curve. The Hugoniot can be determined absolutely through experiments that need to measure only distance and time—that is, velocity.

In the last 10 years, the shock physics program has expanded to include experiments to measure such transport properties as electrical and thermal conductivity as well as sound velocity in shocked materials. The optical properties of the shocked target—the light emitted during an experiment—are also being studied. This additional information is needed to understand the physical processes occurring in a shocked sample.

How Hot Is Hot?

Conservation of momentum, mass, and energy are implicit in Hugoniot curves, but the curves provide no direct way to derive temperature at high pressures. Even after 20 years of study, scientists still do not agree on the melting temperature of iron at pressures above 100 gigapascals (1 gigapascal equals 10,000 times atmospheric pressure at Earth’s surface). Recall that temperature is a critical variable in a material’s equation of state.

Temperatures in a gas-gun experiment can reach as high as 7,000 kelvin, which contrasts with the relatively cool 5,800 kelvin at the surface of the Sun. The only way now to measure such high temperatures during an experiment is with optical pyrometry. A pyrometer measures the radiance—a combination of brightness and color—of the shocked sample. A simple calculation then translates radiance to temperature. That sounds good in theory, but the reality is not so easy.

All measurements of shocked metals and other opaque materials must be taken through a window. A window made of a strong material preserves the surface of the sample at high pressure while allowing light from the sample to pass through to a fiber-optic detector. “But,” notes Holmes, “at very high

temperatures, the window can absorb light and emit its own light, and the window’s presence changes the final state of the sample.” Researchers are just beginning to be able to account for the effects of the window on overall radiance and hence on measured temperature.

Physicist Dave Hare is studying the properties of window materials. Lithium

fluoride has been used as a window material for gas-gun experiments for many years. For many experiments, it is fine. But for planetary studies and some other types of experiments, the window material needs to be stiffer (harder to compress) to be an effective window in gas-gun experiments. Most of Hare’s research centers around sapphire, another window material used for many

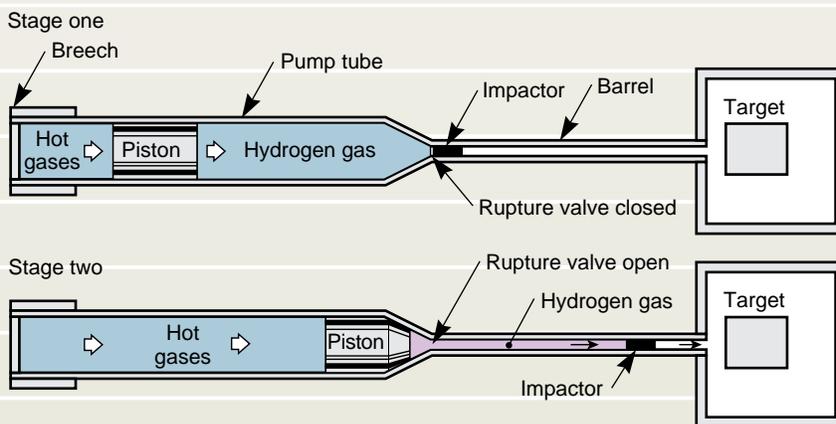
Inside Livermore’s Gas Gun

Livermore’s shock physics group has three two-stage gas guns—one 20 meters long and two about 6 meters long. The larger one is faster and is used for the highest pressure experiments. Both consist of three major parts: a breech containing gunpowder; a pump tube filled with a light gas, typically hydrogen; and a barrel for guiding a high-velocity projectile to the target. When the projectile hits the target, the impact produces a high-pressure shock wave. The guns are driven in two stages, first with gunpowder and then with a light gas such as hydrogen, helium, or nitrogen. The smaller guns can also be used as a single-stage gun driven only by gas.

Hot gases from the burning gunpowder drive a heavy piston down the pump tube, compressing hydrogen gas. This gas, the second-stage driving medium, is compressed before the gas breaks the rupture valve. The gas then accelerates a 15-gram projectile down the barrel to a muzzle velocity of up to 8 kilometers per second.

Hydrogen is used as the second-stage driving gas because it produces the highest projectile velocities, ranging from 4 to 8 kilometers per second. When hydrogen is used as a single-stage gun, the velocities of the smaller guns range from 100 meters per second to 1 kilometer per second. Velocities are determined by carefully selecting the gun firing parameters: the type and amount of gunpowder, the driving gas (helium and nitrogen are used for velocities below 4 kilometers per second), the pressure required to open the rupture valve, the diameter of the barrel, and the mass of the projectile.

A wide range of diagnostic equipment is available to study the shocked targets to measure equations of state, thermal and electrical conductivity, wave profiles, optical pyrometry, and spectroscopy.



years by Livermore researchers. “Sapphire should be a great window,” he says. “It is dense and stiff, and its optical transparency at room temperature and pressure is excellent. But at shock pressures above 200 gigapascals, its transparency degrades too much for it to be useful. I’ve been trying to figure out why.”

In one series of experiments, Hare has found that the orientation of the sapphire crystal relative to the direction of the shock wave makes a big difference in determining its light emissions when shocked. Besides providing an understanding of how sapphire stands up to strong shock waves, these data also help to show how strong materials are deformed by shock waves.

Measuring thermal conductivities under high-pressure conditions is not easy. But thermal conductivity measurements of window and sample materials are crucial to deriving accurate temperatures of the sample’s interior. While the pyrometer measures the sample’s surface temperature, the interior temperature is the real subject of concern. Because the sample and the window are usually at different

temperatures when shocked, heat can flow from the hot sample to the colder window, altering the temperature that the pyrometer measures. Once the thermal conductivity of the window and the sample are known, experimenters can correct their data to derive a more accurate temperature of the sample’s interior.

Physicist Jeff Nguyen is tackling another area that is critical to converting radiance data to temperature. In these calculations, emissivity—which measures how effectively a hot body radiates energy—is assumed to be constant at all pressures and wavelengths. Physicists have known that this is not in fact the case but have had no way to determine the precise changes with pressure. According to Nguyen, “To say that emissivity at high pressures is not well understood is an understatement. Right now, there are virtually no data on emissivity at high pressures.”

Emissivity measurements at ambient pressures and high temperatures have been done routinely. But no definitive theoretical or experimental work has been done at high pressure, especially at the pressures produced by shock compression.

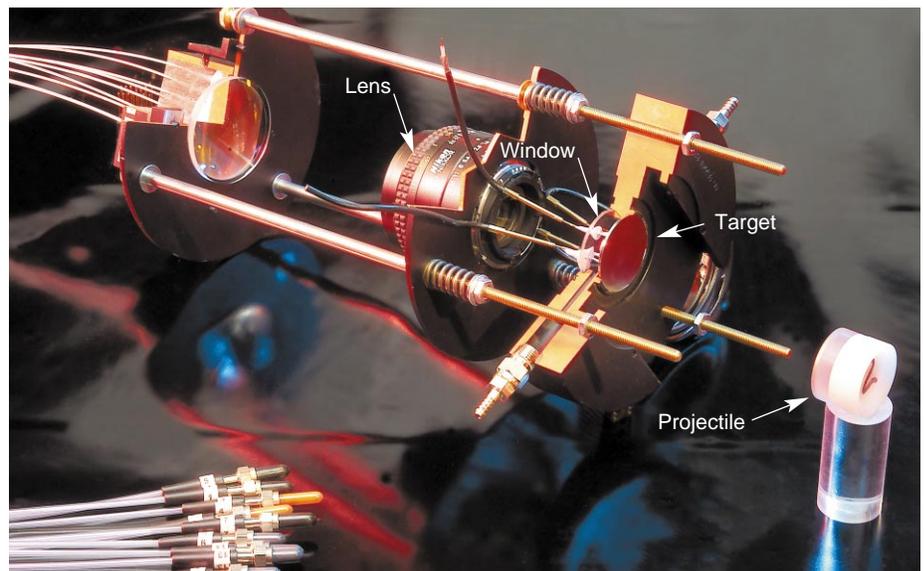
Nguyen’s emissivity experiments of sample materials under shock conditions were performed on metals such as aluminum, copper, and iron. In the experiments, a laser was reflected off a metal target that was shocked, and Nguyen measured the change in the light’s polarization as the metal underwent shock compression. These experiments were the first of their kind. The results are expected to have a major effect on the study of phase diagrams.

“Our goal,” says Holmes, “is to do a shock experiment and know accurately what the temperature inside a sample is. Temperature is a fundamental property. It is, after all, the ‘thermo’ in thermodynamic. But first, we need to know enough about window properties, the emissivity of metals, and the conductivity of windows and metals to separate the sample’s radiance from the window’s.”

Inside Planets

For a brief moment, shock-compression experiments can reproduce the conditions under which some materials spend their entire lives. Iron in Earth’s core is one example, and the interiors of the giant planets are

This cut-away view of an experiment to measure sound velocities in iron shows the level of complexity in target design. Although not seen in detail here, the target baseplate has seven steps. Its surfaces are diamond-turned, and the thickness of the steps is precisely measured. The gap between the iron and the window is filled with bromoform that emits light whose intensity is dependent on the shock it receives. Light emitted from each of the steps is focused into specific optical fibers that send the light into 14 different recording channels. The electrical pins in the gap between the target and the window trigger the instruments that measure the sound velocity through the iron.



another. By reproducing the relevant high pressures, densities, and temperatures with the gas gun, Livermore researchers can reach deep inside the planets where most of the mass is. Convection puts this mass in motion, creating strong magnetic fields that scientists want to understand.

Duplicating the innards of giant planets often requires achieving isentropic or at least quasi-isentropic conditions—that is, constant or near constant entropy. Entropy is a measure of the disorder in a system and relates the total heat in a material to its temperature. In the planets and stars, pressure and temperature increase with depth, but entropy does not change. “A quasi-isentropic experiment comes as close as we can get in the laboratory to duplicating these conditions,” says Holmes.

When stiff plates—stiffer than the target material—are added to the gas-gun experiment, the shock wave will reverberate between them. This is known as a “ring-up” experiment. While a shock experiment always changes the entropy, each repeating shock is weak, and the change in entropy is small. So by compressing the target material with a series of weak shocks rather than one

strong one, the overall change in entropy is smaller and hence quasi-isentropic.

Researchers have found that just a single bounce, called a double-shock experiment, will also produce planetary conditions. Quasi-isentropic experiments, which are at lower temperature and higher density than double-shock experiments, are appropriate for experiments seeking information about the makeup of large planets. Duplicating the conditions at Earth’s core can be achieved with single-shock experiments.

In the hydrogen experiments, liquid deuterium (an isotope of hydrogen with one proton and one neutron in the nucleus) could not be metallized by a single shock. Only when deuterium was compressed to higher densities using a reverberating, quasi-isentropic shock did it become metallic. Many scientists surmise that fluid metallic hydrogen exists deep inside Jupiter and Saturn.

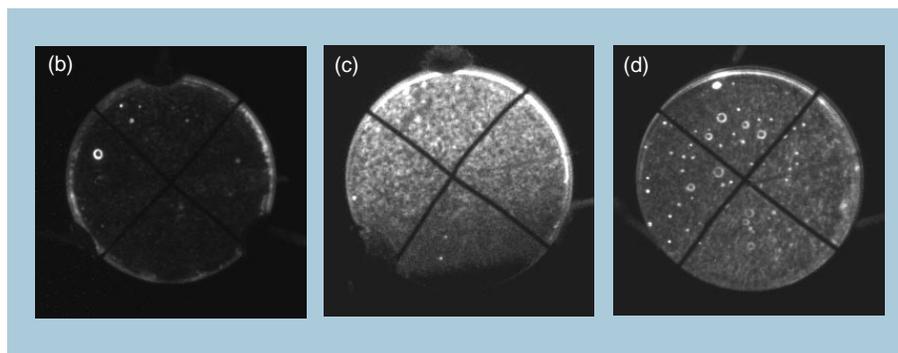
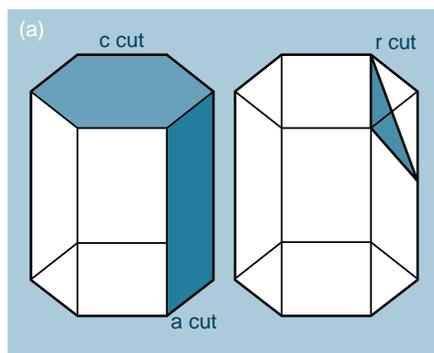
To study the core of our own planet, Nguyen worked on a series of experiments with iron samples to determine the melting pressure at Earth’s core. Geophysicists combine Nguyen’s results with those from other experiments to build the melting curve for iron. From this melt line, they can

determine the temperatures at the boundaries between the core and the mantle and between the inner solid core and outer liquid core.

In single-shock experiments at shock pressures up to about 400 gigapascals, Nguyen measured sound velocities, which change with changes in pressure and temperature. When a material melts, its sound velocity decreases abruptly by 10 to 15 percent. Nguyen found such a decrease in iron near 220 gigapascals, indicating melting. Other metals exhibit a similar drop in sound velocity at the solid–liquid phase change.

What they have not found is just as significant. Twenty years ago, a similar sound velocity experiment suggested an additional solid–solid phase transition at 200 gigapascals, potentially complicating the iron phase diagram. Nguyen’s results simplify the iron phase diagram and prove lower temperatures at the core boundaries than previously thought. These results are also important given the lack of agreement in the scientific community about the melting point for iron at high pressures.

Physicist Ricky Chau and his colleagues are studying the interiors of



A series of experiments demonstrated that the orientation (that is, “cut”) of a sapphire crystal relative to the direction of the shock wave can affect its light emissions when it is shocked. (a) The various ways that a crystal can be cut. (b), (c), and (d) Emission intensity from three cuts of sapphire at similar pressures. The r cut (b) emits significantly less light than the other two orientations at a given pressure, suggesting that the r cut might make a better shock-compression window because it makes less of its own light and thus tends not to mask the light from a shocked sample of the material of interest.

the giant planets Uranus and Neptune. These planets are thought to have a three-layer structure: a small rocky core; a thick layer of “ice” composed of water, methane, and ammonia comprising two-thirds of the planetary mass; and an outer atmosphere of molecular hydrogen and helium. The ice is actually a warm, dense fluid with pressures ranging from 30 to 600 gigapascals and temperatures from 2,500 to 7,000 kelvin. The ring-up method takes temperatures and pressures to those closely matching the interior.

These experiments study the electrical conductivity of the planetary ices. The goal is to use changes in the electrical conductivity to reveal the state of the interior fluids. For example, the convection of conducting fluids deep inside the giant planets is a reasonable explanation for the generation of the strong planetary magnetic fields. To understand the complex magnetic fields, we must measure the electrical conductivity of the planetary fluids.

Using electrodes attached to the gas-gun target, Chau and his coworkers

measured the electrical conductivity of water, which they found to be a relative poor conductor. Physicist Marina Bastea has also examined oxygen, which, like hydrogen, is thought to become a metal at high pressures. Team members are currently studying nitrogen and will be studying methane later this year.

Conductors and Insulators

When Livermore scientists used a quasi-isentropic experiment to produce metallic hydrogen in 1994, they were operating on an assumption basic to high-pressure physics—namely, that all materials will become conductive beyond a certain pressure threshold. Now, Livermore physicists Marina Bastea and Bill Nellis have begun working to produce the opposite phenomenon: using pressure to induce a metal (conductor) to become an insulator. Their studies on metallic lithium could provide the first experimental evidence that this phenomenon is possible.

The theory is that the pairing of atoms of the same element has a strong

effect on the electrical properties of low-atomic-number elements such as lithium. Bastea and Nellis hope to find that under high pressures, monatomic lithium metal (Li) will change into a state in which lithium atoms pair with each other (Li_2). The conduction electrons in the monatomic metal will become localized and nonconducting as the monatomic lithium metal transforms into a diatomic lithium insulator.

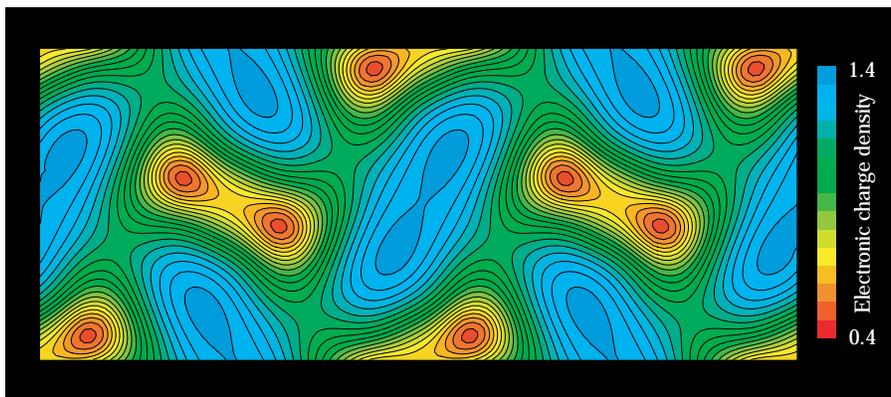
The earlier Livermore experiments showed that hydrogen changes from an insulator to a metal at 140 gigapascals. Monatomic lithium is predicted to become nonmetallic diatomic lithium at 100 gigapascals. So what will lithium hydride, a combination of these two elements, do at elevated pressure?

Lithium and lithium hydride are ideal test cases for the fundamental physics that takes place in highly compressed, condensed matter. They are also relevant for understanding newly discovered astrophysical objects such as brown dwarfs. Both materials have a wide range of technological applications, from high-performance batteries to fuel cells.

More Pioneering Work

Holmes and his team have begun experimenting with new materials for windows such as gallium–gadolinium–garnet, which is twice as dense as sapphire, almost like steel. If it proves to be a good electrical insulator in quasi-isentropic experiments, it will allow researchers to reach much higher densities and pressures in experiments than are now possible.

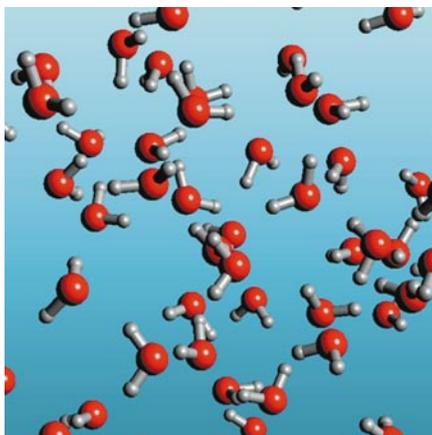
Livermore is also producing some of the first quantum molecular dynamic models of materials under shock conditions. Scientists believe that under high pressures and temperatures, all materials will disassociate and come



Experiments will test whether metallic lithium will become a nonmetal and hence no longer a conductor of electricity at high pressures. Researchers expect to find what is shown in this model, where lithium ions pair with each other (red), and the valence, or conduction, electrons become localized and nonconducting in the interstitial space (blue). (The image is used by permission of J. B. Neaton and N. W. Ashcroft, Cornell University.)

back together quickly. Using Livermore's substantial computational capability, physicist Giulia Galli has modeled the behavior of water under high pressures, calculating where the oxygen and hydrogen atoms are and how hydrogen bonding occurs.

Weapon materials such as uranium, plutonium, and other actinides have not yet been studied directly under shock conditions. But beginning in 2001, a new gas gun in a nested confinement system at the Nevada Test Site will change that. The recently completed Joint Actinide Shock Physics Experimental Research (JASPER) facility is specifically designed to study



The hydrogen and oxygen atoms of the water molecule are clearly visible in this image from one of the first quantum molecular dynamic models of water under high pressure.

the behavior of actinides and other hazardous materials under high pressures, temperatures, and strain rates, approximating the conditions experienced in nuclear weapons. Data from the JASPER experiments will be used to determine equations of state and to validate computer models of material response for weapons applications.

Basic science is at the core of the DOE's Stockpile Stewardship Program, and a full picture of how materials behave when they are shocked is a critical component. Being able to

predict material behavior with full confidence is still some time off. In the meantime, look out—another gas-gun experiment is set to go.

—Katie Walter

Key Words: equations of state, Joint Actinide Shock Physics Experimental Research (JASPER) facility, planetary physics, shock physics, stockpile stewardship, two-stage light-gas gun.

For further information contact Neil Holmes (925) 422-7213 (holmes4@llnl.gov).

About the Scientist



NEIL HOLMES received a B.S. in physics from the California Institute of Technology in 1970 and a Ph.D. from Stanford University in 1977. He joined the Inertial Confinement Fusion program in 1977 and, in 1978, moved to the Shock Physics Group in the Physics Directorate, becoming group leader in 1984. He also holds leadership positions in the Physical Data Research program and is chief scientist for JASPER, a new experimental facility at the Nevada Test Site devoted to shock-wave studies of plutonium at high pressures.

Holmes initially worked on laser-driven shock-wave experiments; most of his current work uses the gas guns. His current research interests include time-resolved spectroscopy of transparent solids and molecular fluids, the thermodynamic properties of materials at extreme conditions, and nonequilibrium phenomena in shock-loaded materials. He is a fellow of the American Physical Society and recently completed a term as national chair of the American Physical Society's Topical Group on Shock Waves in Condensed Matter. Holmes is a two-time recipient of a Department of Energy Award of Excellence.