AGEX I

the explosives regime of weapons physics

Timothy R. Neal

The history of explosives research and above-ground experimentation for nuclear weapons began with the Manhattan Project. During the hectic, almost frantic, war days at Los Alamos, it became clear that, if possible, the fissionable material in the weapon should be plutonium. It was equally apparent that the critical mass of plutonium needed to produce a nuclear explosion would have to be assembled in the weapon through a spherical implosion driven by powerful explosives (Figure 1). Thus from the beginning the development of nuclear weapons was intimately connected with and dependent on developing fabrication, quality-control, and inspection technology for high explosives (explosives with energies greater than that of TNT). Initial experiments in the spring and summer of 1943 revealed, among other things, that for the weapon to work the design of the explosive charges and the timing of their detonation would have to achieve a precision hitherto not contemplated. The achievement of those goals left Los Alamos, at the end of World War II, uniquely in possession of the most advanced explosive-fabrication technology on earth and a mission to make nuclear weapons safer and more efficient—a mission that has continued into the present.

For a long period of time, the work on weapons implosions has utilized conventional plastic-bonded high explosives, which could be precisely machined. Improvements were continually made to increase the accident resistance of these materials. The emphasis on safety in nuclear weapon research led to the development of insensitive high explosive (IHE) at Los Alamos. During the 1970s the Laboratory pioneered the use of IHE in nuclear weapons designs, which dramatically decreased the possibility that the explosives would detonate during accidental insults. Most modern weapons are designed to incorporate insensitive explosives. An IHE—such as triaminotrinitrobenzene (TATB)—can be dropped from great heights and will shatter but not explode. If exposed to fire in an accident, TATB will burn, but it is extremely unlikely to undergo a transition from burning to deflagration or detonation. Even when exposed to high temperature, extreme pressures, or shocks, these materials resist explosion. Thus, they can be handled quite safely with simple precautions.

In addition to safety, the stability and reliability of nuclear weapons in the nation’s stockpile have been ongoing concerns. Scientists and engineers have continued to study the compatibility of materials contained in weapons during long-term storage and to develop new materials for weapons components. The development of new materials has even led to applications in the commercial sector. For example, a high explosive developed in the weapons program, nitrotriazolone (NTO), is under consideration for use as a gas producer in automobile air bags.

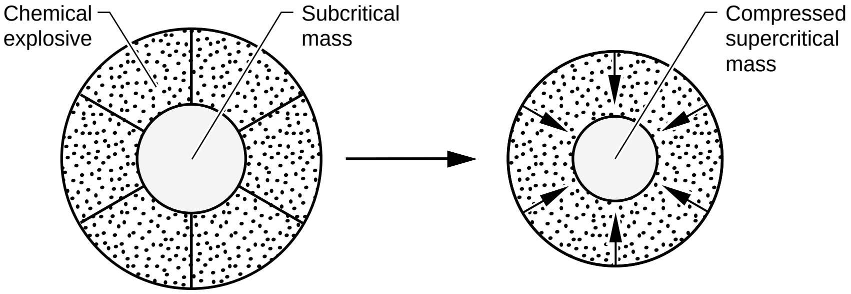


Figure 1. Explosive-driven Implosion
Explosion of a fission weapon is initiated by the implosive force generated by the detonation of a layer of high explosive surrounding the fissile fuel. The detonating high explosive compresses a subcritical mass of fissile material to form a supercritical mass that then rapidly releases nuclear energy through an uncontrolled fission chain reaction.

Research on Safety and Performance of High Explosives

The end of the Cold War has led to increased emphasis on safety. An overriding worry is that an accident might cause the explosive in a nuclear weapon to release its energy, thus causing the assembly of a critical mass and the production of some sort of nuclear yield. Even if a nuclear yield is totally averted through inherent design features, the explosive-energy release might still disperse radioactive plutonium across the countryside. Nuclear weapons have long been designed to avoid or drastically reduce such threats. For example, all weapons in the stockpile are inherently “one-point” safe; that is, the initiation of the explosive at some random point will not produce a nuclear yield. Weapons have also been tested against the raging inferno of a jet-fuel burn to assure their safe response should, for example, a bomber loaded with nuclear weapons catch on fire. However, during the Cold War, as we stood eyeball to eyeball with the Soviets, certain low risks were considered to be more tolerable. Now that the Soviet threat is retracted and our current intent is to dismantle or store needed nuclear arms rather than brandish them, the public deserves even greater assurances about safety. Accident analyses have therefore been extended to address extremely low-probability accidents. Complex, multiple-accident scenarios now being considered include the possibility that after a bomber loaded with nuclear weapons catches on fire, another large plane crashes into it. Can the new “wooden” insensitive high explosives withstand both the high temperature and the severe impact that would be involved in such an accident?

In order to predict the response of explosives in various accident scenarios, research has been under way to further understand the detonation process in high explosives. Unlike gasoline, which must be mixed with the oxygen in the air in order to burn completely and rapidly, high explosives contain enough oxygen to undergo extremely rapid and complete exothermic (heat-producing) chemical reactions. The high explosive is said to undergo detonation if the chemical reaction propagates by compressing the material ahead of it and reaches 90-percent completion within a few millionths of a second. Such rapid reactions produce strong shock waves.

The detonation of a high explosive is typically initiated by a small shock wave that strongly compresses the explosive at a point, causing it to heat up and burn. The exothermic chemical reaction happens so rapidly that the pressure of the reaction products compresses the fuel around it causing that fuel, in turn, to heat up and react, and so the detonation proceeds to spread out from the point of initiation just like a spherical wave. This compression-driven reaction travels at supersonic velocities and is called a detonation wave. The leading edge of the detonation wave is a shock front; that is, there is a discontinuity in pressure, temperature, and density across the front. The pressures built up in the gaseous reaction products behind the shock front are typically on the order of a few hundred thousand atmospheres, and the temperatures are typically between 2000 and 4000 kelvins.

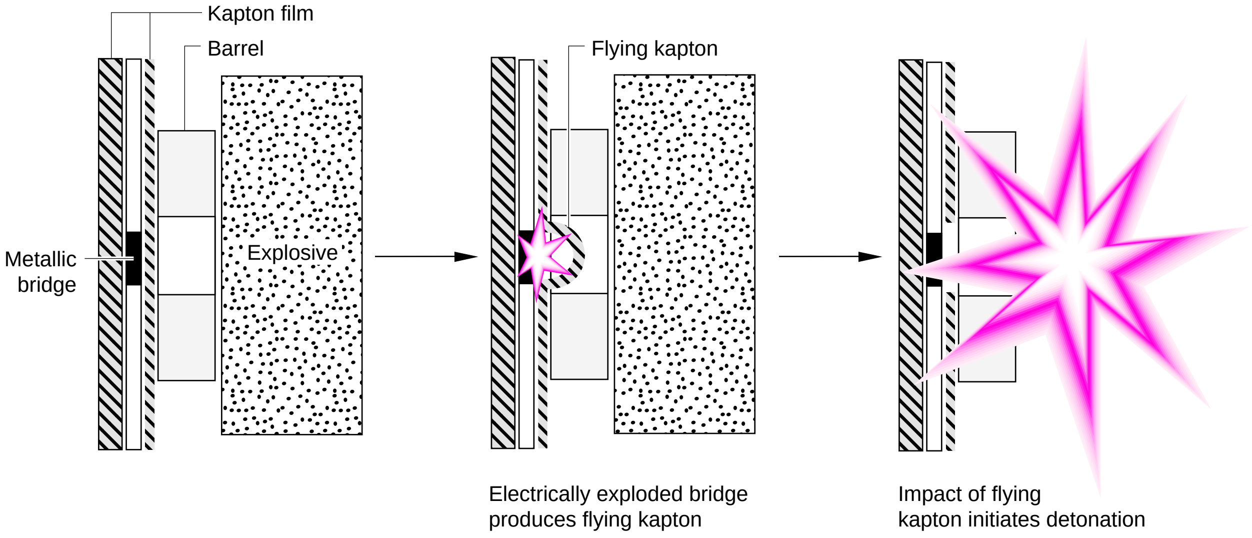
Most accidental insults to a nuclear weapon would not produce shock waves that could initiate the detonation of high explosives. However, exposure to fire along with the impact of a crash might initiate a deflagration, a burn front that propagates by heat conduction rather than compression and therefore proceeds about a million times more slowly than a detonation. A deflagration in explosives and propellants might, however, build up into a full-scale detonation.

The deflagration-to-detonation transition is a significant safety consideration in all industrial, military, and nuclear weapon applications of high explosives and propellants. A comprehensive study of this problem involving a consortium of university and government laboratory participants is under way, and the results of the study are being incorporated into engineering codes for predictive design and safety assessment of nuclear weapons. When the deflagration-to-detonation process is properly understood, we can effect safety measures to guard against even a low-risk accident.

The most important thrust of current explosives research is to develop better models of deflagration and detonation through a combination of experimental and theoretical work. Many advances were achieved in modeling the detonation of conventional high explosives. The fact that chemical reactions in these materials can be considered to occur instantaneously simplifies the modeling of the detonation wave. In contrast, the reaction times of insensitive high explosives are slower and seem to depend on their location inside the explosive charge. Thus the modeling of detonations in IHE has been a far more difficult problem. Through a very strong experimental program scientists have been able to confirm theoretical predictions concerning the behavior of insensitive high explosives, in particular, that reaction rates are strongly accelerated by increases in temperature and pressure. The results of these experiments on reaction rates have been used to develop more precise models of the initiation and detonation of insensitive high explosives and to better understand the effects of reaction rates on the sensitivity of the explosive to heat and impact.

Good models of deflagration and detonation are essential because the set of possible accidents is too broad to test each directly. Growing computing capabilities make it possible to use basic models to simulate the behavior of explosives even in complex geometries. Thus the wave of the future emphasizes carefully selected benchmark experiments to characterize explosive behavior followed by the linking and extension of those results through numerical simulations on supercomputers.

Los Alamos scientists are extending their historic mission in high explosives research to discover at the molecular level what an explosive is and how it works. This fundamental research enlists sophisticated spectroscopic experimental techniques to learn what holds the explosive molecules together, how they come apart during initiation and detonation, and how the released energy builds up the pressure and temperature of the gaseous reaction products so they can do useful work (for example, drive the implosion of a metal



Electrically exploded bridge produces flying kapton

Impact of flying kapton initiates detonation

Figure 2. The Slapper Detonator
A detonator initiates detonation of a high explosive by creating a short, high-pressure pulse in the explosive. Illustrated here is the operation of a standard detonator called the slapper. An intense pulse of electrical energy causes the metallic bridge to burst. The burst drives the kapton film down a short barrel that cuts the film like a cookie cutter. When the piece of flying kapton hits the explosive, it generates a sufficiently strong pressure pulse to cause the explosive to detonate.

sphere). Such studies improve the ability to predict how a new explosive will behave and may also lead to an improved first-principles approach for prescribing explosives with specific desired characteristics. Collaboration of theorists and organic chemists at Los Alamos has recently led to the discovery of a new class of insensitive high explosives that, unlike previous explosives, are very rich in nitrogen and contain much less carbon and oxygen. The first of these to be synthesized, LAX-112, is less sensitive than TNT and produces a more powerful detonation than TATB. Work is continuing to find an explosive within the new class that is even more insensitive but retains the high performance of LAX-112.

The design and engineering development of systems to initiate the detonation of high explosives components is also a part of explosives work. These initiation systems use electrical capacitor discharge units to explode a bridgewire and thereby create a high-pressure pulse in a small region of the explosive. Recent advances in initiation systems include improved safety features. For example, the requirements for stored electrical energy are much lower, and traditional exploding bridgewires have been replaced by flying slappers (Figure 2). Emphasis on improved safety has also led to the development of safer explosives for initiation systems.

The next generation of initiation systems will be based on even safer detonators. Laser-driven slappers or direct optical deposition will create the shock waves that initiate detonation. In more traditional systems metal wires were coupled to the detonator; hence, those wires could feed electrical pulses to the detonator from lightning or other accident sources. In contrast, the new optical power sources cannot be triggered by external sources in any accident scenario.

The disposal of high explosives and propellants that are removed from weapons systems and the environmental redemption of waste from explosive and propellant manufacturing are technologies of prime current interest. Research and development on safe, environmentally acceptable methods for explosive and propellant disposal are under way at Los Alamos and involve interdisciplinary collaborations among many parts of the Laboratory. Methods ranging from base hydrolysis to biological degradation and supercritical water oxidation are under investigation. In the latter, the explosive is broken down into innocuous gases that can then be released.

Above-Ground Hydrodynamic Experiments with High Explosives

The demonstrations in 1943 that an explosive-driven implosion of a metal sphere or cylinder was possible opened up to study the behavior of matter under the extreme pressures, shocks, and temperatures generated by high explosives. This specialized science is termed hydrodynamic testing because solids and metals seem to flow like liquids when driven by the detonation of high explosives.

Firing sites are the laboratories for hydrodynamic testing. Because each experiment self-destructs during a test, the entire experiment must be rebuilt before it can be repeated. Scientists therefore cast about continually for ways to obtain more experimental data from a single experiment. In spite of the commonplace descriptor, “hydrodynamics,” nothing is taken for granted. Every aspect of the broad subject of detonations, the interaction of gaseous explosive products with inert materials, and the possible effects of material strength on the resulting flows is examined extensively. In a common type of experiment, a metal plate is placed in contact with the high explosive, and the high explosive is detonated with the goal of determining how effective it is at pushing on the metal plate. The pressure exerted by the detonating explosive is typically about a million times greater than atmospheric pressure—much higher than the yielding strength of any ordinary metal—and causes the metal to move rapidly, covering distances of a few millimeters in a millionth of a second. Early diagnostics consisted of electronic gauges and high-speed optical motion picture cameras that took a few pictures at the rate of a million pictures per second.

In addition to the experiments with metal plates, experiments were also carried out on weapons assemblies containing surrogates for the fissile material. Such experiments allowed measurements to be made on the early stages of implosion. The results were then used to calibrate computer simulations of weapons implosions that included the behavior of the fissile material.

In the 1960s, a major new diagnostic was added to the repertoire—flash radiography. The technique involves the use of a high-energy electron beam to produce extremely short-duration bursts of x rays. During a hydrodynamic test a single x-ray burst passes through the rapidly moving test object and is recorded on film. The resulting x-ray image

Figure 3. PHERMEX
PHERMEX and its associated image-analysis tools have been continually upgraded and maintained as the premier high-energy radiographic facility in the world. A radio-frequency linear accelerator directs a pulse of 30-MeV electrons to a tungsten target where the energy of the electrons is converted into bremsstrahlung radiation. This burst of x rays is used to make radiographic images of hydrodynamic tests involving high explosives. The photograph shows the thick cylindrical reinforced concrete bunker that houses and protects PHERMEX from the blasts generated during a hydrotest. Woven-steel blast mats covering one end of the bunker are adjacent to the explosive firing point. Electrical signals generated by the hydrotest begin their journey to the recording equipment underground in the structure shown in the lower portion of the photograph.

of the test object effectively "freezes" the motion of explosive-driven weapon components. Such radiographs are analyzed, in great detail, to determine whether the behavior of the weapon components agrees with theoretical predictions.

The machine called PHERMEX (pulsed high-energy radiographic machine emitting x rays) was built mainly for such weapons-system hydrodynamic testing—or hydrotesting, as we call it (Figure 3). PHERMEX was the country's first such facility and was, in certain respects, ahead of its time. It contains a large radio-frequency linear accelerator that produces a beam of relativistic electrons with energies of 30 MeV. The beam is directed at a tungsten target where the energy of the electrons is converted into bremsstrahlung radiation, most of it in the x-ray range. Through continual redesign and upgrade programs PHERMEX and its associated image-analysis capabilities have remained the premier high-energy radiographic capability in the world. Because flash radiography does not perturb the experiment in any way, it yields an accurate measure of whether the explosive performance matches theoretical and engineering predictions.

At first flash radiography stood alone as an isolated diagnostic. But because of the high cost of such experiments, electronic and optical diagnostic capabilities were soon added to the PHERMEX firing site. Thus began our current approach to hydrotesting: diagnose each experiment as thoroughly as possible to get the most return for the investment and to maximize the understanding of total system behavior.

This philosophy continues into the future with the construction of the new DARHT (dual-axis radiographic hydrodynamic test) Facility. Dual axis means that the facility has two x-ray machines that produce x-ray bursts from two directions (Figure 4). At present the images are captured on x-ray film or specialized storage media residing in a recoverable cassette that wards off blast and shrapnel damage. Only a tiny fraction of each x-ray burst actually penetrates the hydrotest object to record an image on the detector, so extensive image-analysis techniques are needed to quantify the resulting pictures. If the two bursts are generated at different times, the resulting images allow determination of velocities of the material in the interior of the test object. As an alternative, the two pictures can be taken at the same time but from different positions to give a "stereoscopic" view that yields a type of three-dimensional image. Finally, there is the option of orienting one x-ray machine to one area of a hydrotest to obtain the best possible resolution and orienting the other machine to a completely different area for similar reasons.

The biggest advance in measurement techniques in the last decade has been the development of quantitative radiography. Radiographs are no longer just pictures of items going hither and yon with distance scales superimposed for measurements. Radiography is now able to determine the density of compressed materials, the location of material interfaces to submillimeter precision, and the computer-assisted tomographic (CAT) reconstruction of interior sections of a distorted object. The latter process is analogous to the CAT scans used in the medical field (Figure 5).

Progress has also been made in other types of diagnostics. Electronic measurements have now attained temporal resolution of a billionth of a second, and hundreds of them may be made during a single hydrotest. Ultrafast color motion-picture cameras are now joined by electronic cameras that are over ten times faster. Lasers are being used as interferometers to precisely measure the velocity of surfaces (see “Line-imaging Laser Interferometer for Measuring Velocitues”). The laser light can be transmitted and returned to detectors through fiber optics, a method that allows measurements to be made in hard-to-reach places. Laser interferometers have traditionally been used to measure the velocities of only a single point on a surface. With the help of image analysis techniques, measurements can now be made along an entire line of a test object. Measurement along a line within an axially symmetric object translates into a continuous high-precision velocity map of an entire surface. In another technique microwaves are propagated through microminiature cables that bend around obstructions. The crushing of these cables as the detonation proceeds yields microwave interferometric measurements of the positions and velocities of shock and compression waves. A selection of these techniques is regularly applied to each hydrotest to measure the position, velocity, and condition of material surfaces as well as the propagation and pattern of wave-like disturbances.

The thrust for the future in hydrotesting is increased precision and all-encompassing diagnostics. Because nuclear testing will no longer be available as the final arbiter, our computational models and codes must be tightly tied to those phenomena that can be measured. In addition, those measurements must be made more universal to elucidate not just the behavior of surfaces but that of interiors as well. Even surface measurements must attain a new degree of sophistication that will yield information about temperature and material breakup.

The explosives AGEX activities must rise to a new role in the nuclear defense activities of the Labo-

Figure 4. Plan of the Proposed DARHT Facility

A major new initiative in the explosives AGEX program is the design and construction of a dual-axis radiographic hydrodynamics test facility. This high-intensity flash x-ray test site will contain two high-energy linear induction accelerators at right angles to each other. The x-ray bursts will be ten times more effective than those available at PHERMEX, enabling flash radiography of dense objects. The two distinct x-ray bursts will be used to generate radiographs of a single hydrotest at different times and with orthogonal views. The extension to the rounded end of one of the machine buildings will contain extensive capabilities for optical diagnostics. The electronic diagnostic equipment for DARHT, like that for PHERMEX, will be located underground near the firing site.

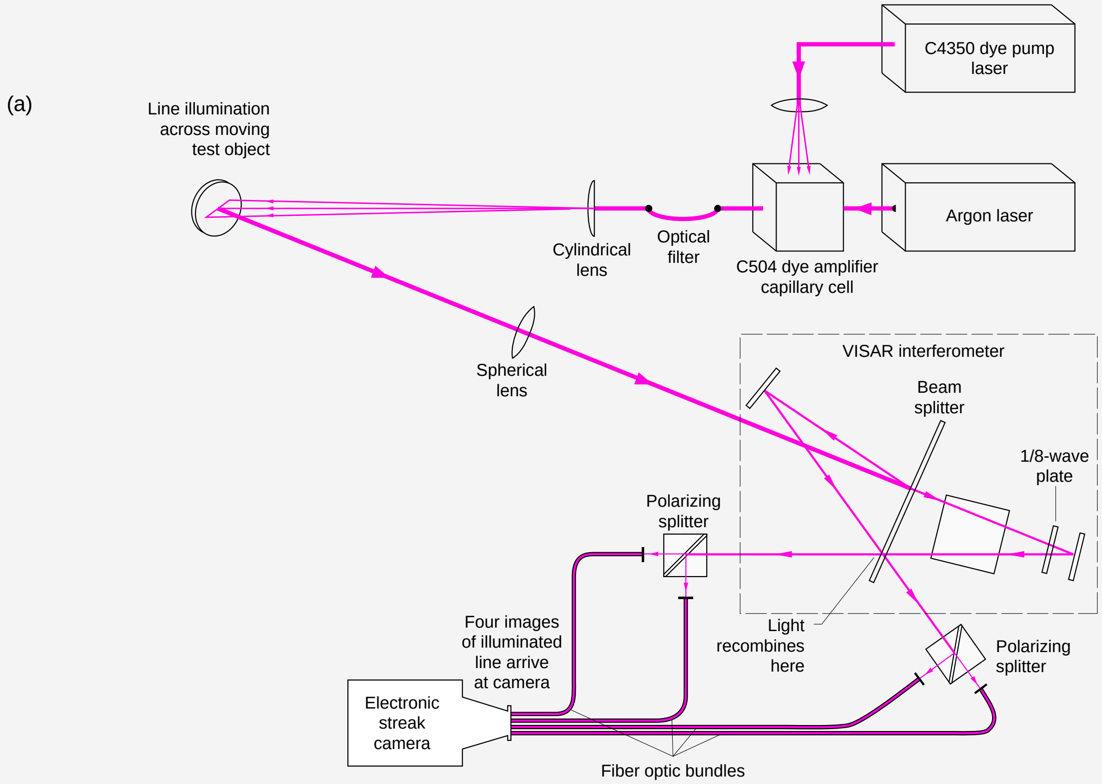
Line-imaging Laser Interferometers for Measuring Velocities

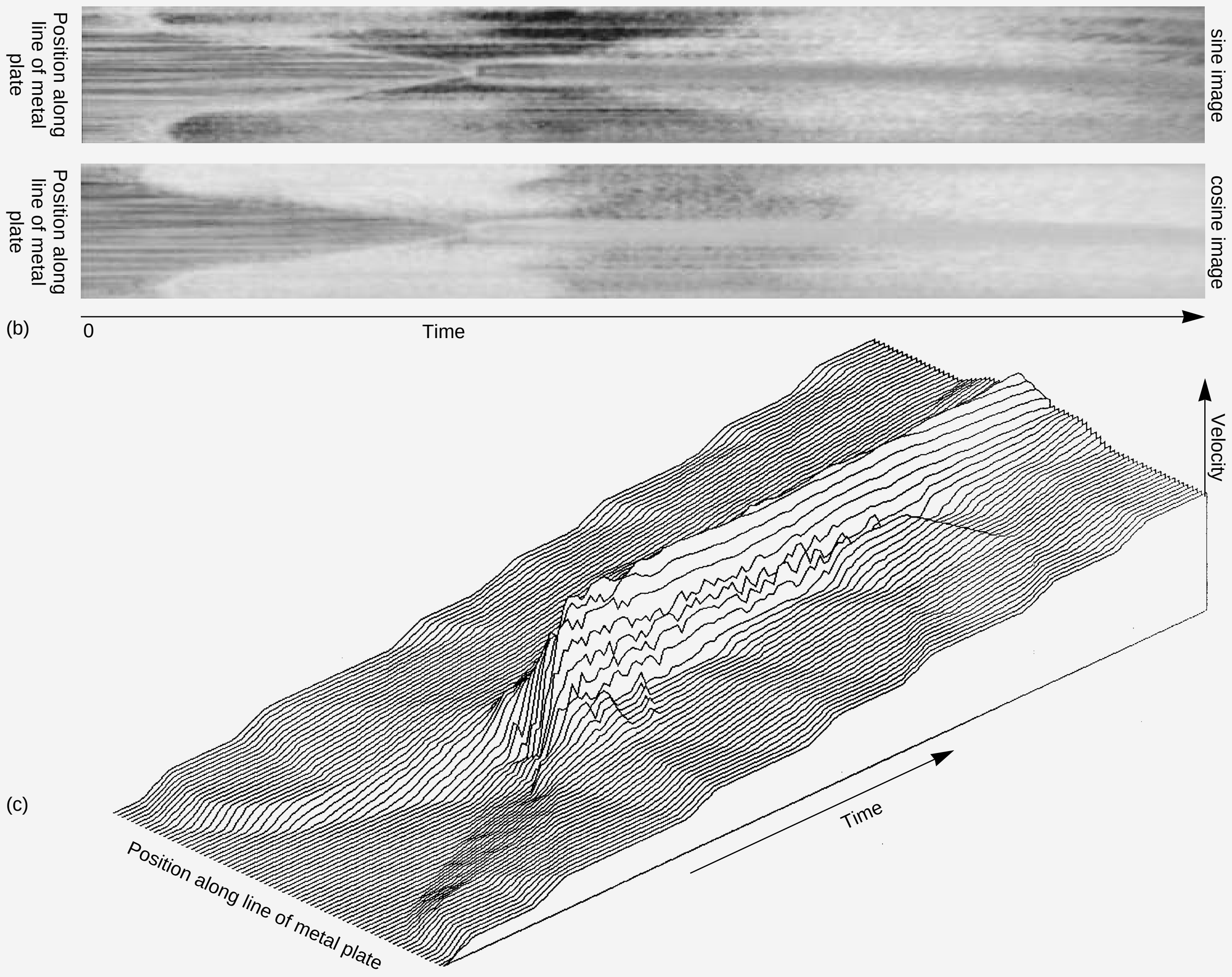
Willard F. Hemsing

Hydrodynamic tests create hostile conditions in which high pressures can easily compress solids and accelerate materials to velocities of several kilometers per second. Among the advanced diagnostics for hydrodynamic tests at the Laboratory is our line-imaging VISAR (Velocity Interferometer System for Any Reflector). The VISAR measures the velocities of points along an illuminated line on a fast-moving test object. The instrument exploits the fact that when laser light is reflected from a moving surface, the wavelength of the light is Doppler-shifted in proportion to the velocity of the point that reflects it. The VISAR employs optical interference to generate bright and dark bands of light called interference fringes. The fringes oscillate between bright and dark as the test object accelerates. The VISAR measures velocity by accurately determining the number of whole and partial oscillations that occur as the test object accelerates. Its useful product is a continuous velocity history for all the points that are visible in the image.

(a) Our line-imaging VISAR uses a cylindrical lens to focus laser light onto a line on the test object. Conventional optics image the illuminated line through a special wide-angle Michelson interferometer, where a retardation plate delays the vertical polarization component of one beam by a quarter of a wavelength. As a result, when the beams are recombined to produce interference, the fringes of the vertical polarization component are shifted and their oscillations lag behind those of the horizontal component. Specifically, the intensities of corresponding points in the horizontal and vertical components depend on the sine and cosine, respectively, of the velocity at each point on the target. Polarizing beam splitters separate the horizontal polarization component from the vertical component where light exits from each side of the interferometer. This separation produces two pairs of images of the interference intensities along the illuminated line. The two images for each polarization are simply negatives of each other.

Fiber-optic bundles transmit the four images to the photocathode of an electronic streak camera. The





camera rapidly sweeps the images across a charge-coupled device that digitizes them into a microcomputer. Later, we subtract one image of each polarization from its negative to double the signal and cancel optical noise. Analysis of the images yields the velocity histories of many points in the line as a continuous function of time.

The VISAR's sensitivity to acceleration, instead of to velocity alone, best accommodates measurements of velocities from 100 meters per second to over 20 kilometers per second. Its recording time can vary from milliseconds to nanoseconds; the length of the line it observes can range from 0.3 to 30 millimeters across the target surface. Because it records pictures with their great capacity to store information, our line-imaging VISAR can capture many times more data than conventional VISARs. We have found its ability to simultaneously record large quantities of information relating different points on a test object extremely advantageous. This is most useful in measurements in which velocity gradients are important, and in tests that destroy expensive hardware, especially when test-to-test variations are important. Although our line-imaging VISAR is versatile, its use is precluded when smoke blocks its optical path or when the test-object surface loses light reflectivity.

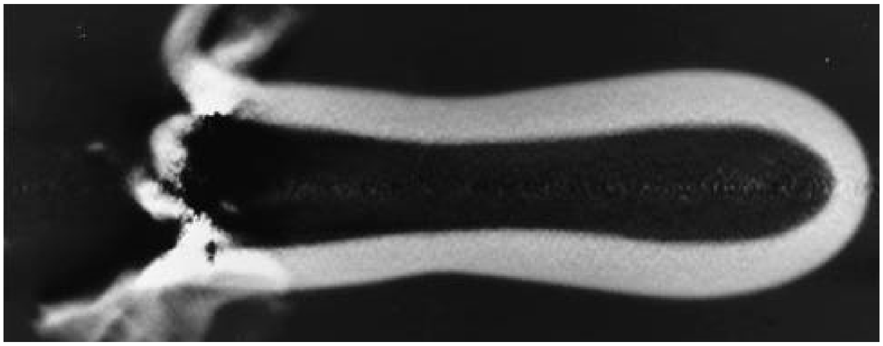
(b) The sine and cosine interference images from an experiment in which two converging detonation waves, produced by an explosive initiated at two separate points, drove a metal plate. Triangles extending across the left third of the images are the edges of interference fringes as they responded to the acceleration of the plate. A change from dark to bright, corresponding to an increase in velocity of 200 meters per second, is visible in the cosine image.

(c) An isometric plot of velocity, deduced from the photograph in (b), as a function of position along the illuminated line and time. The "cliffs" at the lower left indicate the acceleration of the metal as it was driven by the two converging pressure waves. The ridge extending from the center to the upper right is a region of high velocity caused by the pressure enhancement where the waves collided. ◻

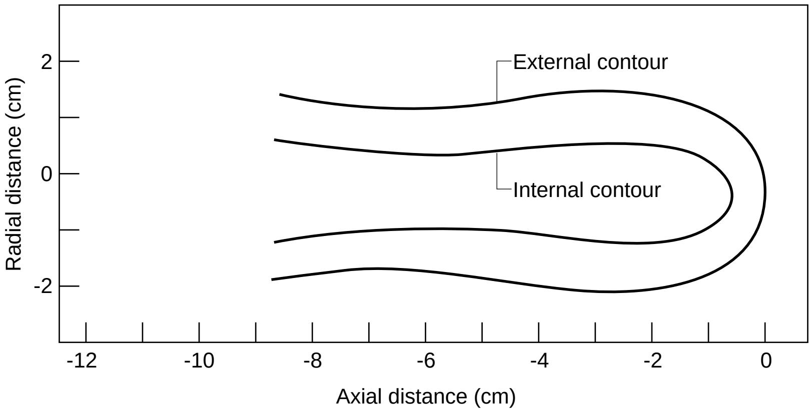
ratory and of the nation. Our capabilitites in explosives characterization, hydrodynamic modeling, and technology development are a special resource to the national materials science community, to U.S. industry, and to the conventional defense community. They are a unique and critical resource to the nuclear weapons community. As availability of under-ground nuclear testing fades, above-ground hydrotesting will become the keystone for nuclear weapon design, qualification, and safety assessment. ■

Figure 5. Quantitative Radiography

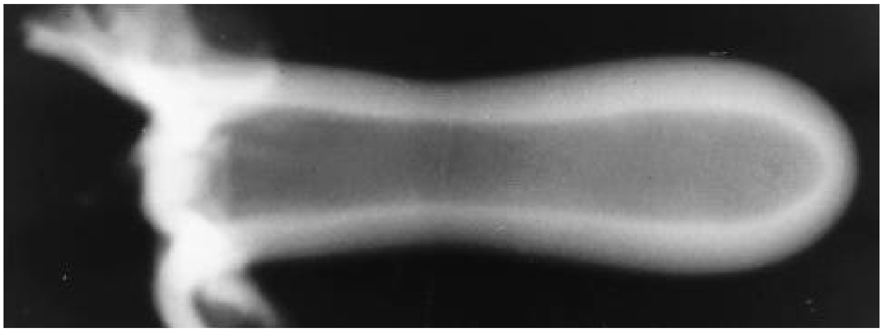
When metals are subjected to the shock pressures and temperatures created by the detonation of high explosives, they seem to flow like liquids. This figure shows images of an explosively formed penetrator made of copper during its high-velocity (2.4 kilometers per second) flight. The penetrator was originally a cone-shaped piece of copper backed by high explosive. The force of the high-explosive detonation shaped the copper into the form shown here.



(a) This radiograph is the average of four different radiographic films of the penetrator in flight. Of interest here is the detailed shape of the inner cavity. The lighter areas represent greater material thickness.



(b) The line drawings of the internal and external contours of the penetrator were estimated by a least-squares fitting of an analytical model to the x-ray film densities. In the forward portion of the penetrator, where axial symmetry is high, the edges of the contours are thought to be accurate to within 0.2 millimeter.



(c) This cross-sectional view of the penetrator is a computer-assisted tomographic (CAT) reconstruction of the interior of the penetrator made from a high-quality radiograph like the one shown in (a). The gray scale represents material density. The combination of good edge location and density reconstruction results from a high-quality original radiograph and excellent image-analysis capabilities. The knowledge of both edge location and density variation is critical to the interpretation of hydrodynamic experiments.

Timothy R. Neal has been Division Leader of Expolosives Technology and Appliations since 1991. He joined the Laboratory in 1967 as a staff member with the Flash Radiograph Group. In 1979 he served as Program Manager for the Confined Testing Program, and in 1980, he was Associate Division Leader for Dynamic Testing. From 1981 until February 1990 he served as Group Leader for Hydrodynamics, where he oversaw the consolidation of groups involving flash radiography, image analysis, and hydrodynamics. He served as Adjunct Associate Professor of Physics at New Mexico State University, instituted the continuing U.S./United Kingdom exchange in weapons hydrodynamics and the U.S./France exchange in image analysis, and was instrumental in developing the Dual Axis Radiographic Hydrodynamics Test (DARHT) construction project.