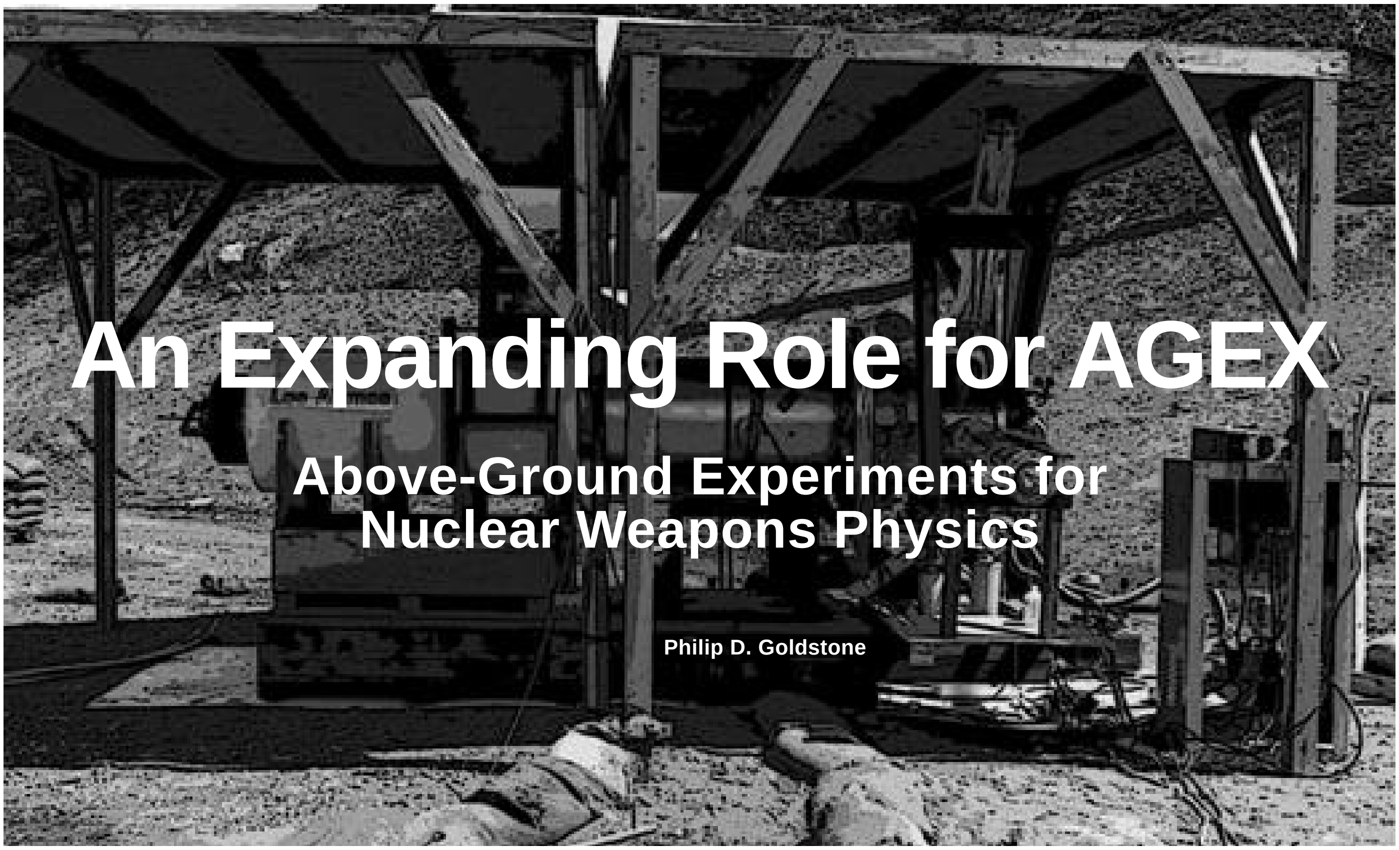


An Expanding Role for AGEX

Above-Ground Experiments for Nuclear Weapons Physics

Philip D. Goldstone

Procyon, the high-explosive pulsed-power generator at Los Alamos

For the last fifty years U.S. expertise in nuclear-weapons design and engineering was a natural by-product of an active development and testing program. With the end of the cold war, the development of agreements to retire most of the U.S. and former Soviet weapon stockpiles, and plans to phase out U.S. nuclear testing by 1996, the way the nuclear weapons program has operated is changing dramatically. However, nuclear weapons will remain a presence in the world for the foreseeable future, and the U.S. will retain a smaller but very real nuclear capability. We at the weapons laboratories will therefore have a vital responsibility—that of long-term stewardship of the stockpile, including continued assurance of reliability and safety. Since the weapons remaining in the stockpile will age, eventually we will have to provide competent assessments of the need to modify or replace aging weapons or components. This role will continue indefinitely into the future and beyond the career lifetime of many of today's weapon scientists.

Imagine, twenty years from now, a military commander or a member of a stockpile-surveillance team noticing that one of the weapons being stored has changed in appearance. They will want to know, “is this still safe, and would it work if needed?” They will call the Laboratory and ask the experts regarding this weapon. Will they be able to rely on the answer they get? A competent technical capability—including the honed expertise and judgement of weapon designers and engineers—is the principal element required for the assurance and stewardship of whatever nuclear stockpile the nation retains. At Los Alamos, where over 80 percent of the weapons that are expected to remain in the stockpile were designed, this responsibility is particularly important.

Without nuclear testing we will simply not be able to maintain today's level of competent judgement. The challenge we now face is to continue to exercise our weapons R&D expertise so that we retain—as much as possible—the ability to assess our own systems (and the nuclear capabilities of others), if we are without any fully integrated nuclear tests and without ongoing development programs. It will be necessary, but not sufficient, for the scientists and engineers involved in this enterprise to do research; the research itself must stress their judgement in weapons science and engineering. Furthermore, to prevent losing capability within a generation, these research programs must be technically interesting to attract and train new scientists and engineers.

In the absence of underground testing, a high premium will be placed on predictive computational capability for design and engineering of weapons. If our computer-simulation capabilities were perfect, then, in principle, actual testing would not be required for us to be confident of the performance of an aging, modified (for improved safety, for example), or even redesigned device. Computational-simulation capabilities are simply insufficient for this challenge, despite many years of development and the ongoing revolution in high-performance computing.

Therefore, part of the strategy for meeting the dilemma posed by a cessation of nuclear testing is to develop higher-performance computing capabilities and to exploit those capabilities by running more accurate and more predictive codes.

Although the weapons-design codes may be viewed as an "archive" where design physics is contained for future designers to use, continued comparison of code predictions against experiment—*reality*—is required to provide validation of the codes and the designer's judgement. The physics, materials behavior, and engineering associated with nuclear weapons is extremely complex. In a matter of moments, weapon components are brought from their normal physical state to the most extreme conditions found in the solar system. It is the act of continually testing both the codes and the designers against experiment that develops and maintains expertise and that prevents theory and reality from diverging. As long as a simulation code contains implicit approximations and assumptions, its value is intimately tied to the judgement of those who use it and interpret its output. A divergence of theory and reality can (and often does, in many human endeavors) result in a false sense of confidence in computation or design judgement that is potentially disastrous. This is the principal underlying reason for regularly performing nuclear tests, even if we could anticipate never having to modify a stockpiled weapon again. Therefore, in the absence of underground testing, appropriate "aboveground experiments" (AGEX) must be vigorously pursued.

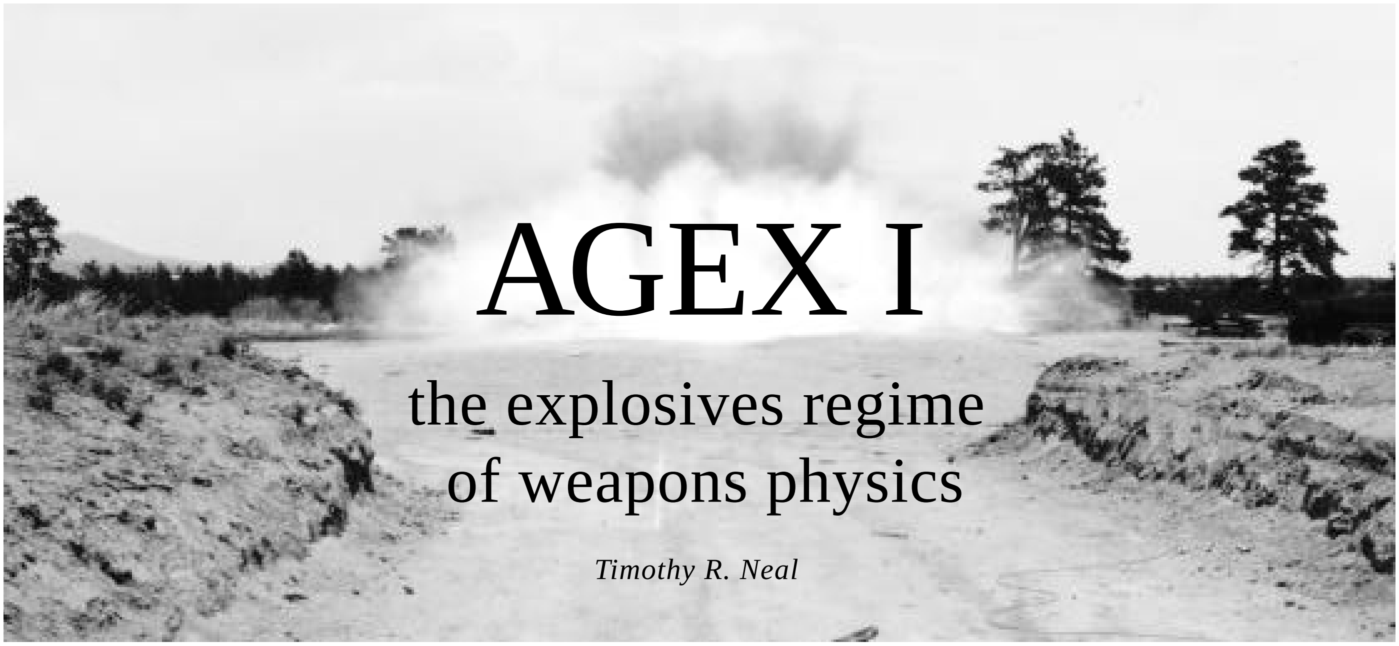
The role of experiments is, first, to provide the physics data and the underlying physical models to improve the predictive nature of the codes. Second, and possibly more important, experiments provide ongoing validation and exercise of weapons capability and judgement. A proper mix of experiments will even actively involve the fabrication, engineering, quality assurance, and fielding skills vital to weapons capability. Third, only a technically stimulating research program that combines experiment with theory is capable of attracting and retaining quality scientists and engineers in the weapons effort. Finally, in its own right, experimental capability—the ability to measure and interpret data, whether that data derives from an underground weapons test, an aboveground experiment, or from other sources such as nonproliferation activities—is an essential component of U.S. nuclear weapons stewardship.

The following two articles discuss the two physical regimes that must be addressed in experiments related to weapons design. The "explosives regime" (or AGEX I) includes the physics and chemistry of explosives as well as the behavior of matter subjected to the pressures, shocks, and temperatures that may be achieved with typical high-explosive configurations. For example, the behavior of heavy-metal assemblies compressed by high explosives is an important element of weapon design and engineering.

Above-ground experiments directly applicable to many (though not all) important aspects of the high-explosives regime of weapon design are possible without a nuclear explosion. The principal example is that of hydrodynamic testing, including flash radiography of high-explosives-driven assemblies. The DARHT (Dual-Axis Radiographic Hydro Test) facility is the single most important new AGEX capability for the future confidence in the U.S. stockpile. Explosives characterization as well as hydrodynamic testing is discussed in "AGEX I—The Explosives Regime of Weapons Physics."

The second physical regime that must be addressed by experiments is the "high-energy-density" (or AGEX II) regime, which is typically achieved only after the initial production of nuclear energy. It involves temperatures from tens to thousands of electron-volts or eV (1 eV is equivalent to 11,600 kelvins) and pressures greater than 10 megabars (1 megabar equals 1 million atmospheres). Technical issues in the high-energy-density regime include radiation flow and the interaction of radiation with matter; radiation hydrodynamics and hydrodynamics at extreme pressures; nuclear cross sections and neutron interactions; and the behavior of dense plasmas.

Whereas the explosive regime can be more or less directly accessed at full scale, achieving the high-energy-density regime over anything approaching the full spatial and time scales of a weapon would imply an extraordinary amount of energy, comparable to that of a nuclear explosion. Although this is clearly neither achievable nor desirable in an aboveground experiment, various pieces of the physics can be accessed and studied by using an appropriate set of specialized facilities. The efforts to develop and use such facilities for the study of the high-energy-density regime are discussed in "AGEX II—The High-Energy-Density Regime of Weapons Physics." ■



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.

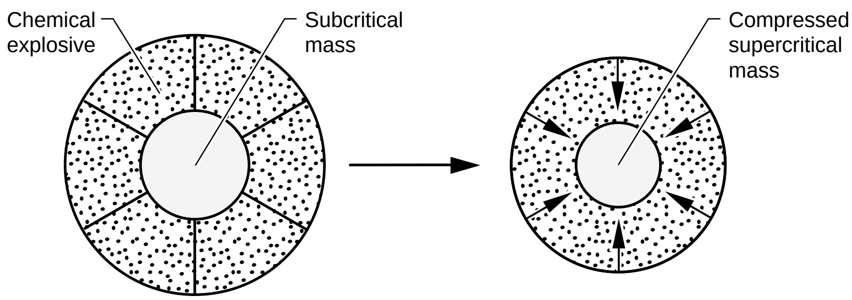


Figure 1. Explosive-driven Implosion
Explosion of a fission weapon is initiated by the implosive force generated by the detonation of a layer of high explosive surrounding the fissile fuel. The detonating high explosive compresses a subcritical mass of fissile material to form a supercritical mass that 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

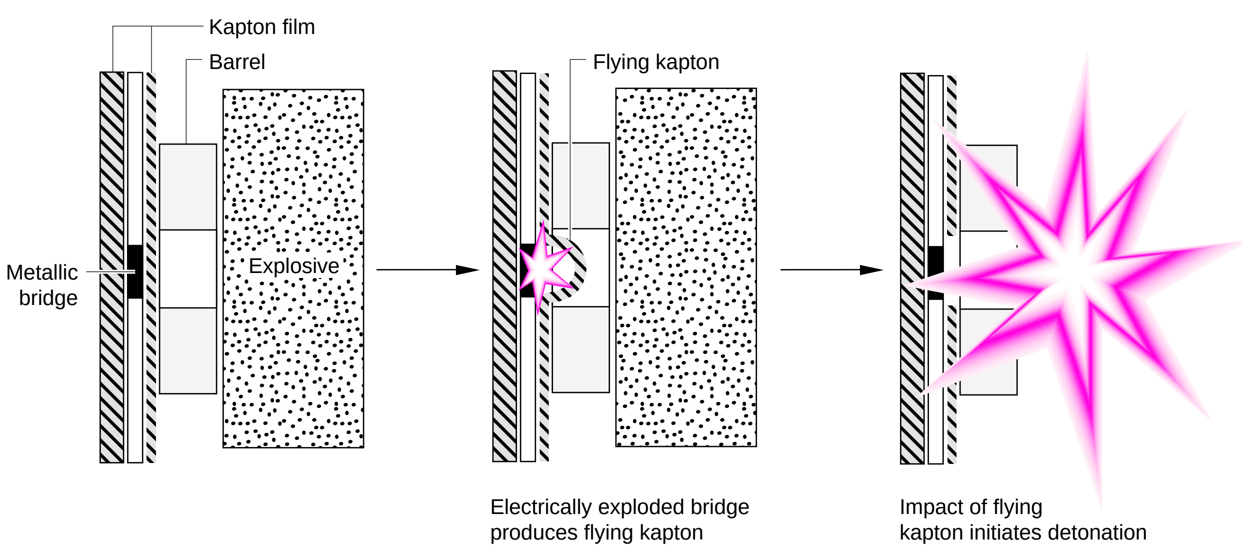


Figure 2. The Slapper Detonator

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 Velocities"). 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

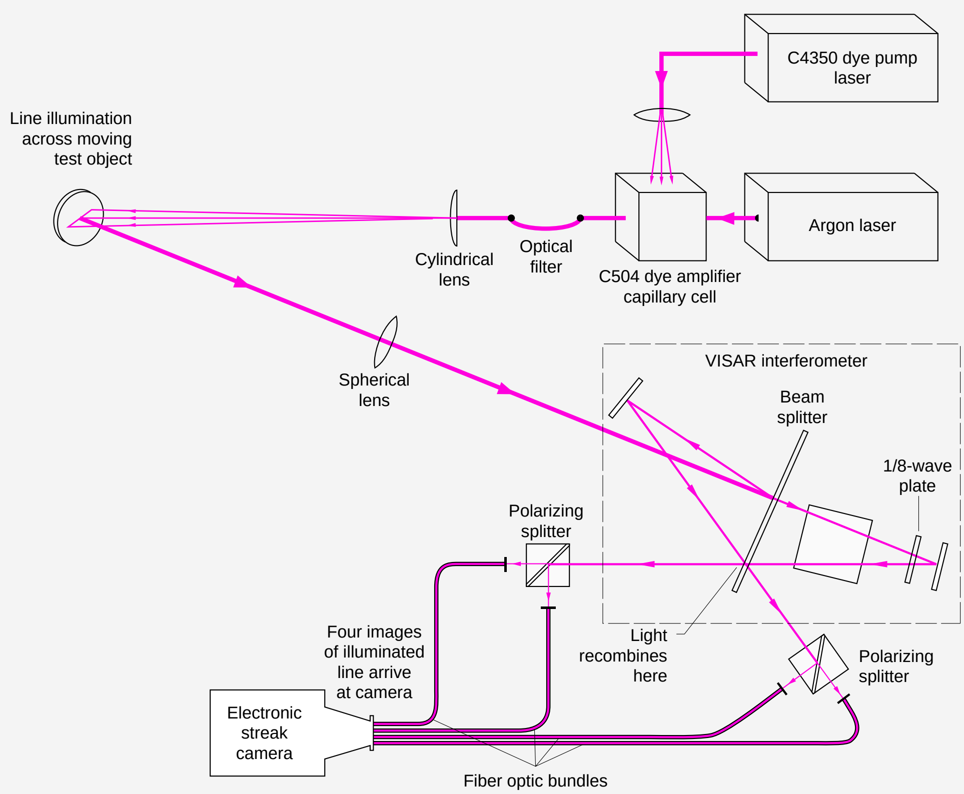
Willard F. Hemsing

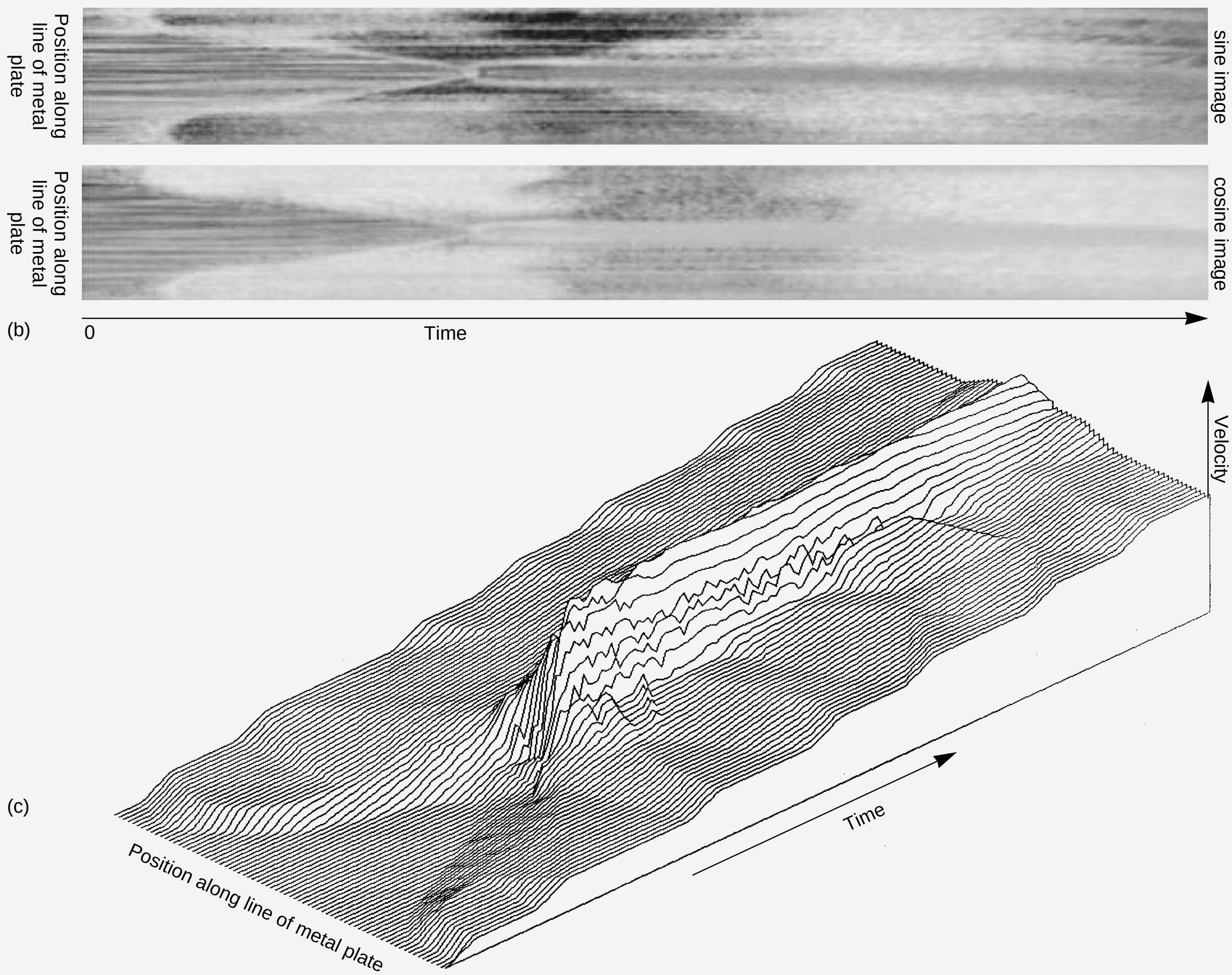
Hydrodynamic tests create hostile conditions in which high pressures can easily compress solids and accelerate materials to velocities of several kilometers per second. Among the advanced diagnostics for hydrodynamic tests at the Laboratory is our line-imaging VISAR (Velocity Interferometer System for 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

(a)





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.

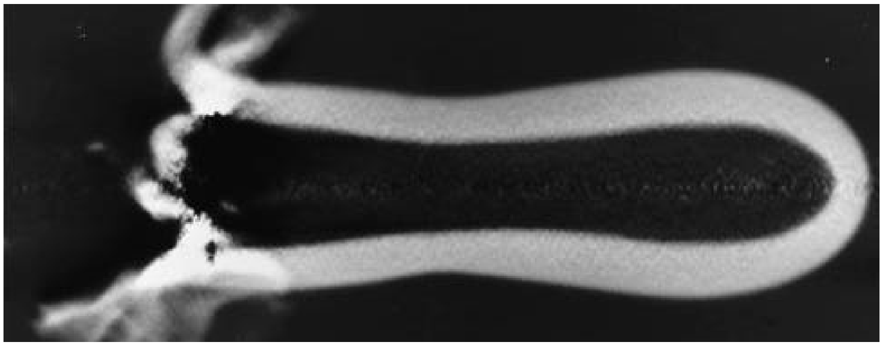
(b) The sine and cosine interference images from an experiment in which two converging detonation waves, produced by an explosive initiated at two separate points, drove a metal plate. Triangles extending across the left third of the images are the edges of interference fringes as they responded to the 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. □

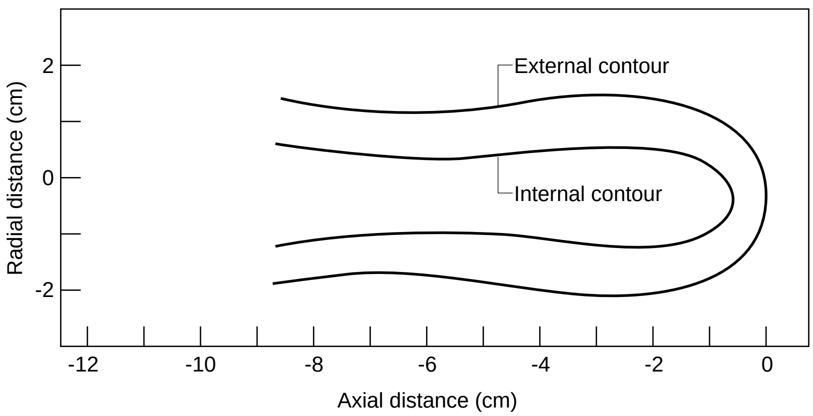
ratory and of the nation. Our capabilitites in explosives characterization, hydrodynamic modeling, and technology development are a special resource to the national materials science community, to U.S. industry, and to the conventional defense community. They are a unique and critical resource to the 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

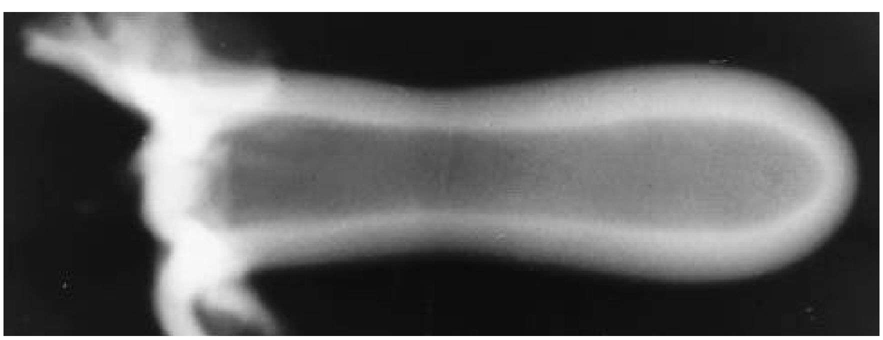
When metals are subjected to the shock pressures and temperatures created by the detonation of high explosives, they seem to flow like liquids. This figure shows images of an explosively formed penetrator made of copper during its high-velocity (2.4 kilometers per second) flight. The penetrator was originally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

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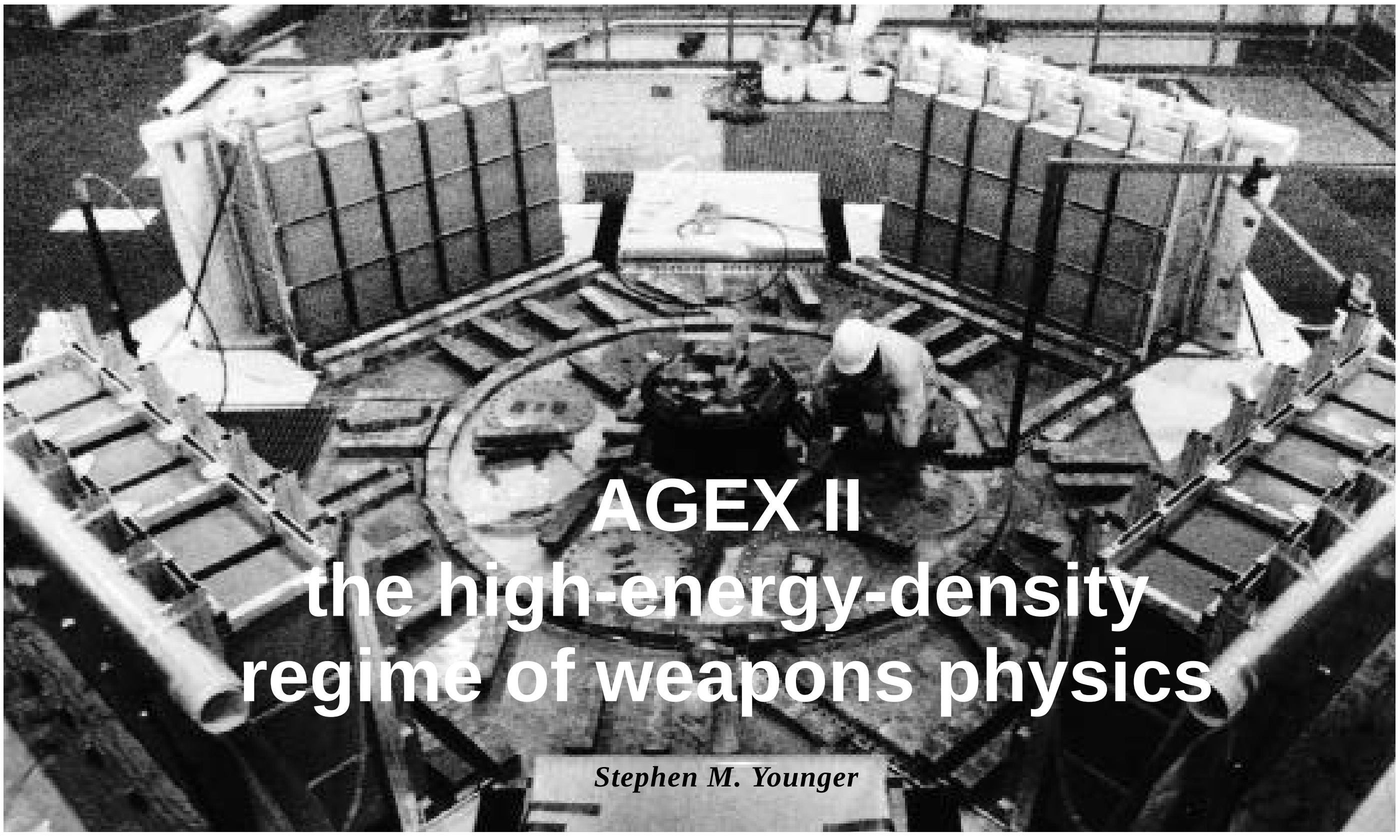


AGEX II
the high-energy-density regime of weapons physics

Stephen M. Younger

The Pegasus II capacitor bank for pulsed-power experiments

Nuclear explosives achieve higher temperatures and pressures than any other object in our solar system. Pressures in excess of ten million atmospheres, temperatures over 1000 electron volts (1 eV corresponds to 11,600 kelvins) and very high densities typify a nuclear explosion. Under these conditions even the heaviest atoms are almost completely ionized, and neutron radiation is so intense that higher-order nuclear processes (such as multple capture) become common. Our knowledge of such extreme energy-density conditions has been gained through a combination of theoretical calculations and experiments performed on actual nuclear explosions. With the reduction in the number of underground nuclear tests, however, our access to these unique conditions has been sharply reduced, and by the end of 1996 it will disappear entirely. There is an urgent need to develop laboratory techniques that will allow us to simulate the conditions found in a nuclear explosive both to provide more accurate information on the physics of matter at high energy density and to provide a vehicle for continued development of the special skills required to maintain an understanding of nuclear weapons.

The Physics of Nuclear Explosives

Nuclear weapons are very complex devices. During the high-explosive phase of the weapon, materials are subjected to pressures of several hundred kilobars and reach temperatures of several eV. These conditions are reproducible in the laboratory and a great deal of data are available to describe material response and hydrodynamic processes at these pressures. (See “AGEX I—The Explosives Regime of Weapons Physics.”) When the fissionable material in the weapon reaches a critical mass, however, a chain reaction occurs, which causes the rapid generation of energy. This chain reaction occurs on a time scale short compared to the ratio of the size of the device to the sound speed, so the material does not have a chance to expand during the energy-generation phase. Since the energy cannot go into kinetic energy, it goes into thermal energy, raising the temperature of the material to extraordinary values and thus raising the pressure to many millions of atmospheres.

Laboratory studies of the properties of high-energy-density matter face two major challenges: First, one must reproduce the very high densities and temperatures typical of a nuclear explosion. Second, one must be able to probe the conditions in the sample, usually via an x-ray burst (to probe atomic properties) or a pressure pulse (to probe material equations of state). The energy required to heat a sample is roughly given by $(3/2)nkT$, where n is the density of particles (nuclei plus ionized electrons), k is Boltzmann's constant, and T is the temperature. A simple calculation shows that normal-density uranium at 1 keV has an energy density of about 500 megajoules per cubic centimeter. Even for a sample 1 millimeter across the net energy required is 500 kilojoules, a substantial amount for laboratory experiments. Also, in contrast to fissioning metals, which generate heat internally, laboratory samples must be heated by an outside energy source. The heating takes several nanoseconds, long enough for the sample to begin to disassemble. The resulting density and temperature gradients complicate the interpretation of the experiment. Reducing the density allows one somewhat greater flexibility, since hydrodynamic tampers can be used to keep the material from expanding during the experiment. Unfortunately, low-density samples lack some of the unique aspects of dense plasma. The relevant figure of merit for dense matter is the coupling parameter, Γ, the ratio of the average electrostatic energy between neighboring ions to the average thermal kinetic energy. For low Γ thermal processes dominate and the plasma behaves as an ensemble of individual particles. For high Γ the electrostatic force dominates, the plasma becomes "stiff," and it can even condense into a solid phase. The goal of high-energy-density physics is to produce a sample dense enough to resemble a strongly coupled plasma yet hot enough for the level of ionization to be representative of the material in a nuclear explosive. This requires both raw energy, to heat a sample of significant size, and power, to rapidly heat the sample before it expands to low density.

Examples of High-Energy-Density Physics

	The Sun	Jupiter	High explosives	Lasers	Pulsed power	Nuclear explosions
Temperature (eV)	10^3	1	~1	>100	100	>10^3
Pressure (atm)	10^9	10^6	10^5	10^8	10^7	>10^7
Density (g/cm^3)	10	1	1	100	10	>10

Diagnosing a high-energy-density plasma is also challenging. No material probe can withstand the conditions of a hot dense plasma, so remote measurements are essential. X rays, either those emitted by the plasma itself or those absorbed when an intense probe signal is passed through the plasma, can reveal much about the atomic properties of the material. Strong shock waves can be launched into the sample to determine its equation of state via the measurement of shock and particle velocities. Such experiments are made more complex by the presence of the hydrodynamic tamper or other artifacts of the plasma-containment mechanism.

No single above-ground experimental facility can simultaneously reproduce all of the relevant conditions found in a nuclear explosion. At Los Alamos we have assembled a broad array of high-energy-density facilities, including pulsed-power machines, lasers, and the LAMPF accelerator, that allow us to access a broad range of high-energy-density conditions for the study of physics relevant to nuclear explosives.

Athena: Pulsed Power for High-Energy-Density Physics

In Greek mythology Athena was the goddess of wisdom who carried the thunderbolts of Zeus. At Los Alamos Athena is the program that uses pulsed-power technology to explore high-energy-density physics in support of the nuclear weapons program. The advantage of pulsed power for high-energy-density physics is that many megajoules of energy can be stored in very compact devices and then rapidly delivered to an experiment. The Athena program uses two methods to generate intense electrical pulses: a large capacitor bank called Pegasus II and a high-explosive pulsed-power generator called Procyon.

Capacitor-bank pulsed power. The Pegasus II capacitor bank consists of 144 capacitors wired in parallel and arranged around a central target chamber. Over the course of several minutes, a high-voltage power supply charges the capacitors. Pegasus

II can reach a maximum voltage of about 100 kilovolts and store up to 4.3 megajoules of electrical energy. At full voltage, the power supply is disconnected, and the stored electrical energy is rapidly discharged into a target located in a central chamber. Depending on the switching, the discharge time can be from 0.3 to 6 microseconds. At peak current, around 10 megamps, the power flow in Pegasus II exceeds that produced by the electrical generating capacity of the United States.

The target in Pegasus II experiments is typically a hollow metal cylinder, several centimeters in diameter and a few centimeters tall, oriented with its axis connnecting the two current-carrying electrodes of the capacitor bank. A current I flowing in the cylinder produces a magnetic field

$$B = \mu I/2\pi r$$

(where $\mu = 4\pi \times 10^7$). The interaction of this magnetic field with the drive current results in an inward pressure,

$$P = B^2/2\mu,$$

that causes the rapid implosion of the cylinder. When the Pegasus II capacitor bank at full charge is discharged through a gold-foil cylinder with outer radius of 2 centimeters and wall thickness of 0.1 millimeter, the cylinder implodes in about 6 microseconds. The peak pressure is 1.1 megabar and the peak implosion velocity is about 1.3 centimeters per microsecond.

Pegasus II can be used for three main classes of experiments. Simply discharging the bank through a cylindrical target provides a test bed for studying implosion hydrodynamics and material properties. To study the growth of hydrodynamic instabilites, asymmetric or otherwise deliberately perturbed cylinders are imploded and the results compared to numerical simulations that use various theoretical models for instability growth. The time sequence in Figure 1 shows a side view of a very thin-walled cylinder as it implodes during a Pegasus experiment. The onset of small-scale instabilities, their evolution to larger-scale perturbations, and finally the complete breakup of the imploding shell are clearly visible. We have done a number of experimental studies to assess how instability growth depends on wall thickness, material, and other implosion parameters.

In the second class of experiments, a sample is placed inside the imploding cylinder to study its material properties under extreme pressures and temperatures. An imploding cylinder can compress a sample to a pressure of several megabars. At this extreme pressure the atomic structure of the sample becomes distorted. The forced overlap of atomic orbitals causes changes in the transport rates of heat, charge, and photons. Serious research on those transport phenomena in hot dense matter is just beginning to be pursued. Since the implosions are nearly adiabatic and create high-pressure conditions that last on the order of a microsecond, Pegasus II is an ideal test bed in which to study the structure and dynamics of matter under extreme conditions.

In the third class of experiments, very fast implosions are used to generate intense x-ray bursts. These bursts are needed for a wide range of experiments on radiation transport and the interaction of x rays with matter. When the cylindrical foil implodes to its axis, the kinetic energy of collapse is converted to thermal energy, and the matter in the foil becomes a hot plasma. The matter then rapidly cools by emitting an intense burst of x rays. Kinetic energy is proportional to the square of the velocity, so implosions at higher velocities produce more x rays. Since the magnetic pressure during the implosion is independent of the mass of the foil, the implosion velocity can be increased by reducing the thickness of the foil. Cylindrical

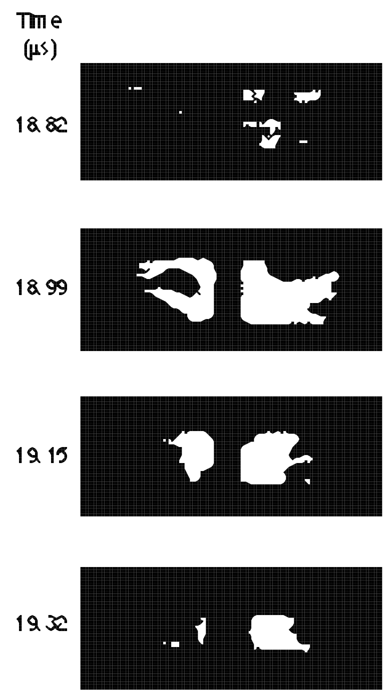


Figure 1. Implosion of a Thin Foil Cylinder at Pegasus II
A side view of the implosion of a 2500-angstrom-thick, 5-centimeter-radius, aluminum cylinder on the Pegasus capacitor bank is shown at various times, with an arbitrary zero time. Note the onset of short-wavelength perturbations at early times, followed by the growth of longer-wavelength perturbations, and eventually the complete breakup of the aluminum foil.

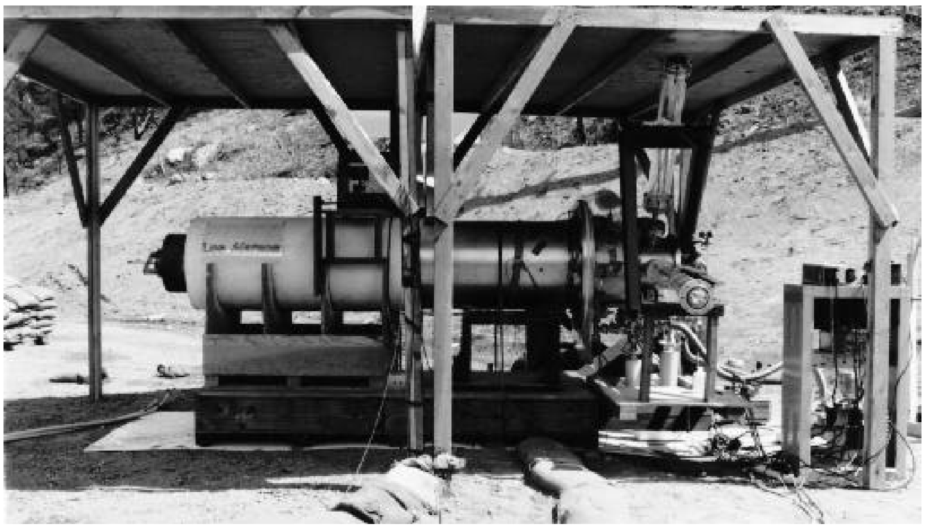


Figure 2. The Procyon High-Explosives Pulsed-Power System
The white cylinder at left is a Mark IX high-explosive generator. To the right is an explosive opening switch, and at the extreme right are the plasma flow switch and the implosion target. The clear tubes extending from the target contain diagnostic equipment.

foils as thin as 2500 angstroms (less than the wavelength of visible light) have been imploded on Pegasus II to velocities in excess of 10 centimeters per microsecond. However, the onset of hydrodynamic instabilities limits the usefulness of very thin foils. The very rapid acceleration endured by these foils enhances the growth of Rayleigh-Taylor instabilities. The foils can become so unstable that they break up before reaching the axis, in which case various pieces of the foil arrive at different times. This prolongation of the arrival of the imploding shell results in a lower effective energy density in the plasma and hence a softer x-ray spectrum. Also, if the implosion velocity is so high that the implosion is over before the capacitor bank has the opportunity to deposit all of its energy in the target, then the resulting x-ray burst will be less intense. Two techniques are available to overcome these limitations. First, by using special switching techniques to reduce the rise time of the bank from several microseconds to several hundred nanoseconds, we can make energy deposition in the cylindrical foil more efficient. Second, by increasing the radius of the foils, we can extend the implosion time. We hope that an optimal combination of the two techniques will maximize the coupling of the energy in the capacitor bank to the kinetic energy of the foil while minimizing the growth of deleterious hydrodynamic instabilities.

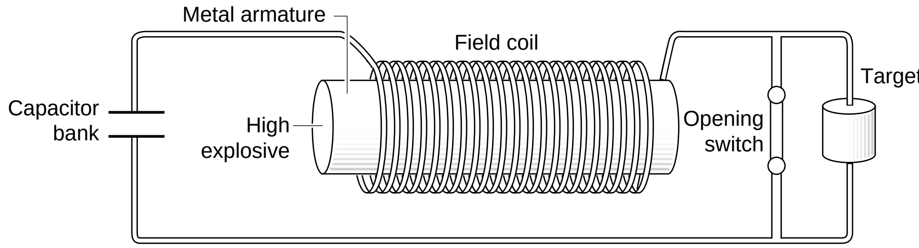
High-explosive pulsed power. Pegasus II produces pressures of megabars and energy densities of hundreds of kilojoules per cubic centimeter in a volume of about a cubic centimeter. The production of significantly higher pressures in a similar-sized volume would require storing tens to over a hundred megajoules of electrical energy in a very large capacitor bank. This can be an expensive proposition. Fortunately there is a relatively low-cost alternative, namely, the amplification of electric power pulses with high explosives. At Los Alamos we have developed a series of high-explosive pulsed-power generators that have produced currents as high as 150 million amperes in compact, relatively low-cost units. The present device, called Procyon (Figure 2), can deliver more than 1 megajoule of energy into an implosion.

Figure 3 illustrates the operation of a high-explosive pulsed-power generator. A small capacitor bank sends a current pulse through a coil wound loosely about a copper cylinder that is filled with high explosives. This current creates a magnetic field in the gap between the coil and the copper cylinder. As the magnetic field reaches its peak value, the high explosive in the copper cylinder is detonated. The cylinder expands, and as it closes the gap between itself and the coil, it squeezes the magnetic field into a smaller and smaller volume and thereby increases the magnetic-field energy. At maximum field compression the switch shown in the figure is opened, allowing the field energy to be extracted in the form of a greatly amplified current pulse that flows through the target.

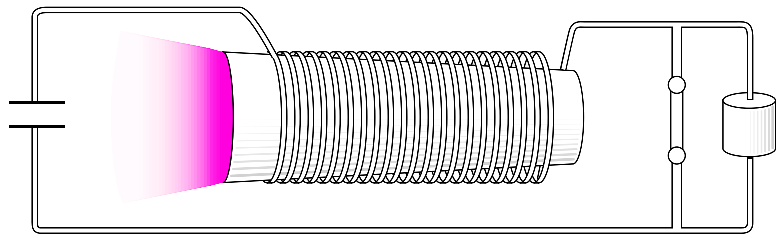
Even though high-explosive pulsed-power generators can produce tens or even hundreds of megajoules of electrical energy in a single pulse at affordable prices, the pulse is several microseconds long, so the power eventually delivered to a target is at most a few tens of terawatts (1 terawatt = 10^{12} watts). At present it is difficult to compress this energy into a much shorter, higher-power pulse, which would be useful for the production of intense x-ray bursts or ultrahigh pressures,

Figure 2. Operation of a High-Explosive Pulsed-Power System

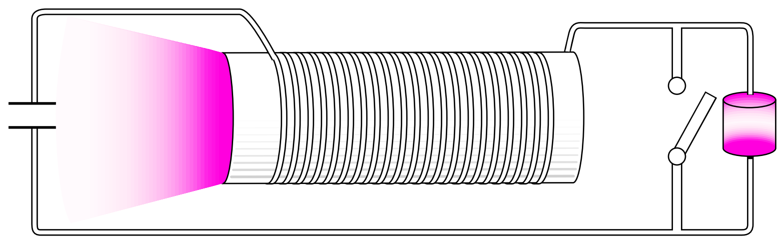
As the capacitor bank discharges through the field coil, the current in the coil generates a magnetic field between the coil and the metal armature. The opening switch is in the closed position, preventing current from flowing to the target.



The high explosive is detonated at one end and expands the armature. The magnetic field is squeezed between the expanding armature and the field coil and greatly increases in magnitude. In this way high-explosive energy is converted into magnetic-field energy. The field energy, in turn, amplifies the current.



At peak compression of the magnetic field the switch is opened and a greatly amplified current pulse flows through the target.



although a variety of options are being evaluated. To reach significantly higher powers, one must employ other technologies more suited to short-pulse generation. Chief among those are high-power lasers.

Lasers: Higher Energy Densities for Shorter Times

Lasers can produce very short, high-power pulses and direct them into small volumes to create very high energy densities. But the current high-power lasers are very expensive energy sources and maintain high energy densities in a target for only a nanosecond or so and over volumes only of the order of a cubic millimeter. In spite of these limitations, high-power lasers have proven to be very versatile in the study of high-energy-density physics.

Trident is a neodymium-doped glass laser at Los Alamos that delivers two simultaneous pulses, each 100 picoseconds long and carrying 100 joules of energy. The laser consists of a very low-energy oscillator that forms the laser pulse, a series of rod amplifiers that increase the energy in the pulse to about 1 joule, and a set of disk amplifiers that provide the final amplification. The pulses are directed into a target chamber outfitted with a wide array of diagnostics, including x-ray and optical spectrometers, framing cameras, and streak cameras.

A Trident 100-picosecond laser pulse focused into a volume a few hundred microns in diameter yields an energy density of over 1 megajoule per cubic centimeter. Although the energy density is higher than that produced in experiments using Pegasus II, our 4-megajoule capacitor bank, the temporal and spatial scales of the experiments are much smaller and very sophisticated diagnostics are required to acquire data. The inertial-fusion program has made impressive progress in diagnostics development, so that it is now possible to obtain x-ray images of experiments with spatial resolution of less than 5 microns and temporal resolution of less than 100 picoseconds.

Trident was designed to be an easy-to-use tool for high-energy-density physics. It can deliver laser pulses with a wide variety of lengths and shapes for different experiments. Trident also has a small third laser beam, which is used to create a short x-ray pulse next to the target. X radiographs of evolving experiments can be obtained from the x-ray pulses and are particularly useful for the study of high-pressure hydrodynamics. Trident pulses, when applied to appropriate targets, can produce shock-wave pressures of several megabars and x-ray pulses of moderate temperatures.

Still higher temperatures over somewhat larger volumes can be obtained on the Nova laser at Lawrence Livermore National Laboratory. Nova, the largest glass laser in the world, produces pulses of up to 40 kilojoules in one nanosecond. We have fielded a number of experiments on Nova related to radiation hydrodynamics and x-ray-driven implosions.

How far can one go in increasing energy density by shortening the pulse length of the laser and reducing the size of the focused optical spot? Another laser at Los Alamos, Bright Source II, is providing the answer. Bright Source II pushes the limits of energy density by directing a relatively small amount of energy (only a quarter of a joule at present, although a 10-joule machine is on the horizon) into an incredibly short pulse that can be focused down to only a few microns. Bright Source II pulses last less than 300 femtoseconds, so that even though it is moving with the speed of light, a pulse is only about 900 microns long. The focused pulses have intensities of more than 5×10^{18} watts per square centimeter, well above pulse intensities produced by Trident or even Nova. The impact of a laser pulse on the surface of a target sample creates pressures of more than 1 gigabar, but only for about one picosecond, after which the sample expands under thermal pressure. (It is interesting to note that the radiation pressure—the pressure due to the momentum of the light itself—is 1 gigabar, which is comparable to the induced thermal pressure in the target.) During such a short pulse the atoms in the target do not have a chance to equilibrate and may not approximate fully the equilibrium conditions found in a nuclear explosion. Nevertheless, Bright Source II can heat thin solid foils to keV temperatures, creating a high-density and very hot plasma. Hence this laser can be used to probe the structure and dynamics of matter at conditions that approach those found in a nuclear explosion. The hot plasma cools both by expansion and by the emission of x rays. Figure 4 shows a typical x-ray spectrum from an aluminum sample illuminated by a Bright Source II pulse. Up to 1 percent of the incident laser energy is converted to line radiation around 2 keV. The line radiation is useful for studying the interaction of x rays with matter.

The extremely short pulses available from the Bright Source II laser also provide an effective means to study very rapid processes, such as transient chemical reactions. In typical chemical detonations several transient molecular species such as OH radicals persist only for a short time but are important in determining the overall energy balance in the detonation products. An experiment is currently underway at Bright Source II to measure the OH radical in a forced detonation—the first such measurement of its kind for an explosive process.

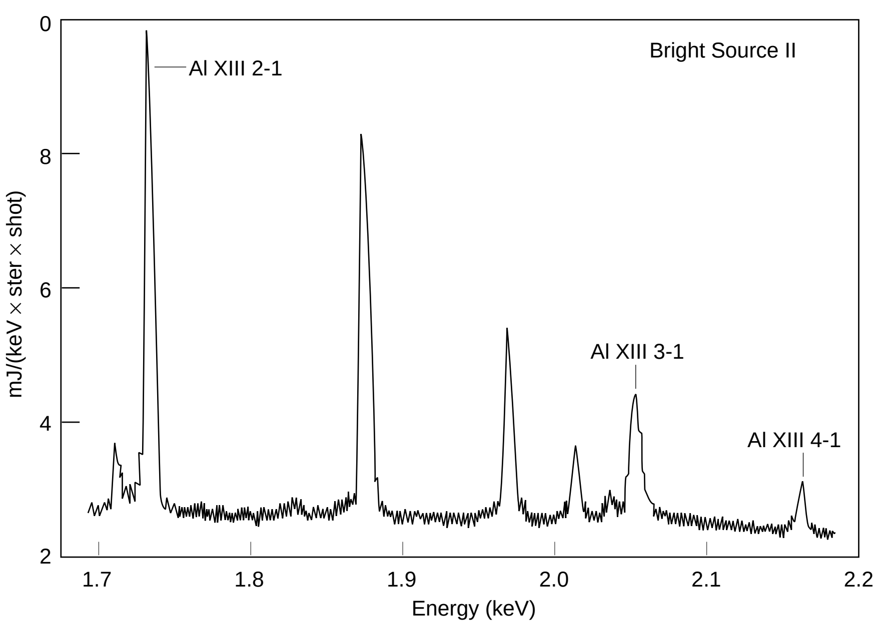


Figure 4. X-Ray Spectrum Induced by a Pulse from Bright Source II
The x-ray spectrum results from the impact of a 0.25-joule, 300-picosecond pulse from the Bright Source II laser on an aluminum foil. The intense lines serve both as a diagnostic of the conditions in the dense radiating plasma and as valuable probes for use in other experiments.

Nuclear Physics at LAMPF

Moving up again in the energy scale, we encounter nuclear energy densities—where the relevant energy parameters are not kiloelectronvolts as in plasmas but megaelectronvolts.

The formation of a critical mass during the detonation of a nuclear explosive and the attendant chain reaction result in an intense neutron burst. Neutrons interact with nuclei through a complex set of scattering and capture processes, some leading to the production of additional neutrons and/or the initiation of fission and others to the production of stable isotopes. To model the dynamics of fission in weapons, we must have accurate descriptions of all of the dominant neutronics processes. The knowledge of weaker processes (such as those involving transient nuclear states) can provide valuable diagnostics on the progress of the nuclear burn and contribute to radiochemical analyses of nuclear explosions. The Laboratory has conducted an extensive series of experiments on nuclear physics important for weapons at LAMPF and other nuclear facilities.

LAMPF is the most powerful accelerator in the world. Although some machines accelerate charged particles to higher energies, none is capable of delivering as many particles per unit time to the target as LAMPF. This capability is important when one wants to study weak processes, including the study of higher-order nuclear cross sections. In addition to the accelerator itself, the LAMPF facility includes several target areas. The areas of particular concern for the weapons program are the Weapons Neutron Research (WNR) facility and the Manuel Lujan, Jr. Neutron Scattering Center (LANSCE).

LAMPF has been extensively used by the weapons program. Fundamental aspects of fission have been studied by examining the relative timing of fission and neutron emission in fissioning nuclei. Angular distributions of neutrons, gamma rays, and fission decay products have been measured to determine the energy and momentum balance in fission. Detectors used in nuclear tests have been calibrated on LAMPF to provide absolute measurements of the neutron flux from the nuclear device. We are currently evaluating new techniques for using proton and neutron sources to image dynamic phenomena in opaque samples.

The Future

The next several years promise to be among the most interesting and productive ever for high-energy-density physics. We have assembled an array of facilities to investigate a wide range of physics issues of importance to the nuclear weapons program. The structure and transport properties of hot dense matter will be systematically studied in a regime where single-atom theories break down and many-body effects are important. The interaction of strong shock waves and x-ray pulses with matter will continue to be studied with the aim of providing quantitative data for use in our computer models of nuclear explosions. Experimental data on hydrodynamics and hydrodynamic instabilities will allow us to validate increasingly sophisticated algorithms in new computer codes, particularly those that will need to be developed to exploit the promise of massively parallel computers.

Each of our capabilities can be extended to higher energies for even more interesting applications. The next advance in Laboratory capacitor banks is Atlas, a 25-megajoule machine that will permit us to study high energy densities over tens of cubic centimeters. The Procyon high-explosive pulsed-power generator will be followed by a more advanced system that will deliver in excess of 200 million amperes. Bright Source III is being designed to produce focused intensities over 10^{20} watts per square centimeter to permit the study of multiphoton x-ray interactions. This intensity is high enough to rip apart the vacuum in the electrostatic field near a nucleus to create electron-positron pairs, literally creating matter from energy. ■

Stephen M. Younger is the Program Director for Inertial Confinement Fusion and High Energy Density Physics at the Laboratory. He received a Ph.D. in theoretical physics from the University of Maryland in 1978. From 1974 to 1982 he performed theoretical studies of atomic processes at the National Bureau of Standards in Washington, D.C., concentrating on electron scattering from atoms and ions. From 1982 to 1989 he was a staff member and group leader at Lawrence Livermore National Laboratory, where he specialized in advanced thermonuclear weapons design, x-ray lasers, electromagnetic weapons, and other defense programs. In 1989 he came to Los Alamos and in 1991 he was named to his present position. In addition to working on defense issues, Younger has continued to contribute to fundamental atomic and plasma physics. He is a Fellow of the American Physical Society and has served on numerous government panels and committees.