Shaped Charges Pierce the Toughest Targets

I N early 1997, Lawrence Livermore successfully tested a shaped charge that penetrated 3.4 meters of high-strength armor steel. The largest diameter precision shaped charge ever built produced a jet of molybdenum that traveled several meters through the air before making its way through successive blocks of steel (Figure 1). A shaped charge, by design, focuses all of its energy on a single line, making it very accurate and controllable. When size is added to that accuracy, the effect can be dramatic. The success of this demonstration at the Nevada Test Site's Big Explosives Experimental Facility would not have been possible without the combination of reliable hydrodynamic codes and diagnostic tools that verify one another.

A shaped charge is a concave metal hemisphere or cone (known as a liner) backed by a high explosive, all in a steel or aluminum casing. When the high explosive is detonated, the metal liner is compressed and squeezed forward, forming a jet whose tip may travel as fast as 10 kilometers per second. Shaped charges were first developed after World War I to penetrate tanks and other armored equipment. Their most extensive use today is in the oil and gas industry where they open up the rock around drilled wells.

Leaving Trial and Error Behind

Early work on shaped charges showed that a range of alternative constructions, including modifying the angle of the liner or varying its thickness, would result in a faster and longer metal jet. These research and development efforts to maximize penetration capabilities were based largely on trial and error. It was not until the 1970s that modeling codes could predict with any accuracy how a shaped charge would behave. While the concept of a metal surface being squeezed forward may seem relatively straightforward, the physics of shaped charges is very complex and even today is not completely understood.

Today, a Livermore team headed by physicist Dennis Baum is continuing the development of shaped charges. Recent research has studied various aspects of their dynamics, including the collapse of the liner, jet formation, and jet evolution as well as the behavior of variously constructed liners. The team performs simulations using CALE (C-language-based Arbitrary Lagrangian-Eulerian), a two-dimensional hydrodynamic code developed at Livermore. When experimental results are compared to the simulations, the team has found that CALE accurately describes the mass

Figure 1. Testing personnel stand behind perforated blocks of armor steel after the early 1997 shaped-charge demonstration at the Nevada Test Site.
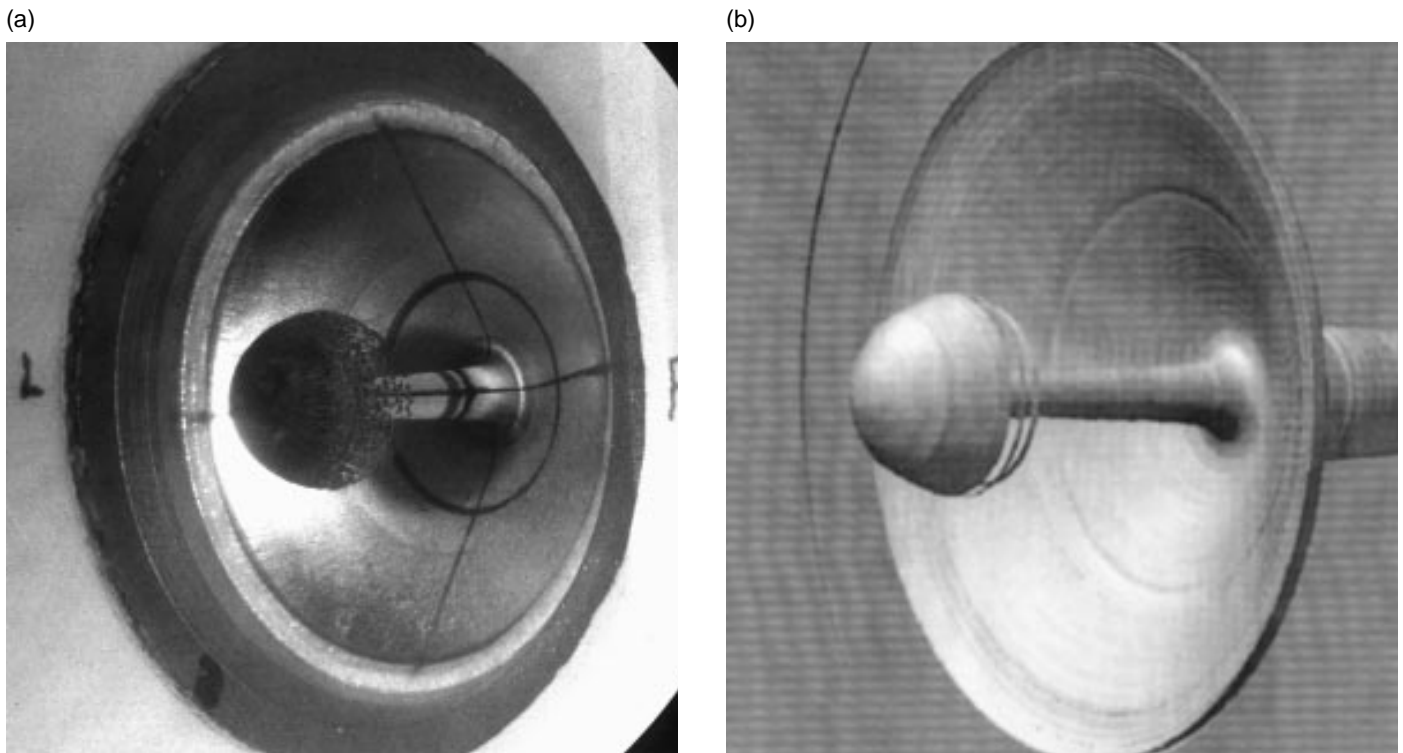
(a)   (b)

Figure 2. These images compare (a) actual experimental results with (b) the modeled simulation and demonstrate the validity of the modeling code. (a) An image-converter camera photograph of a conical, copper shaped charge known as a "Viper" taken at 19.3 microseconds after detonation. (b) The corresponding three-dimensional visualization of the results of the code simulation at the same time after detonation. The grid lines on the jet stem in (a) were drawn on the liner before detonation. After an experiment, researchers study photographs of the jet and use the lines to follow liner collapse and jet formation processes as a function of time.

and velocity distributions of the collapsing liner and resultant jet as a function of time. The code can also reproduce, albeit with less accuracy, various dynamic features of jet development such as the low-density shroud of material that streams back from the jet's tip. This shroud is not uniform around its circumference, and its development is strongly affected by nonuniform distributions of the mass of the jet and other deviations from axial symmetry. The Livermore team uses ALE3D, a three-dimensional code still under development at the Laboratory, to more fully reproduce these details of jet behavior.

Figure 2 compares a computer simulation for an experiment in 1992 with the actual result. The simulation and the results varied by just 1 to 2%. Results from the experiment in early 1997 cited above were similar. With this ability to produce accurate simulations and thus rely on the codes, the team can go on to build similar shaped charges in different sizes for a number of national defense applications.

Diagnosing an Experiment

Livermore scientists use a variety of complementary diagnostic tools during experiments with shaped charges. X-radiography produces shadowgraphs that provide experienced researchers with information about the jet's velocity, density, and mass distribution (Figure 3). The rotating-mirror framing camera, a kind of motion picture camera, can shoot millions of frames in a second. A typical shaped-charge jet-formation experiment lasts less than 30 microseconds, and the framing camera is usually set to record an image about once every microsecond. The exposure time for the framing camera may be anywhere from 100 to 200 nanoseconds, or billionths of a second.

The newest tool is the image-converter (IC) camera, which was developed at Livermore in the mid-1980s. A pulsed ruby laser is synchronized with the IC camera frames to provide illumination of the shaped charge. The electronic image tube that acts as the shutter for each image frame converts the
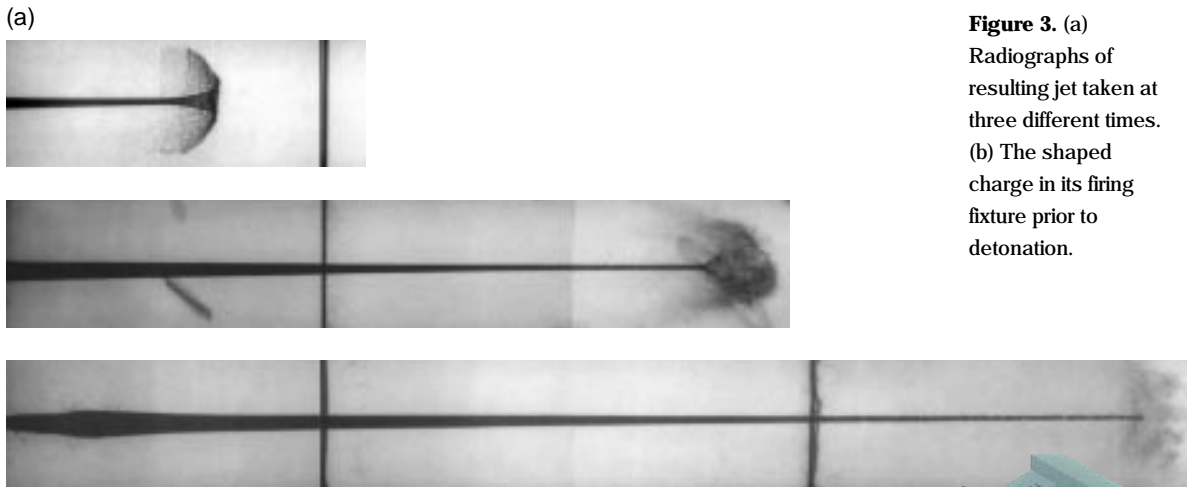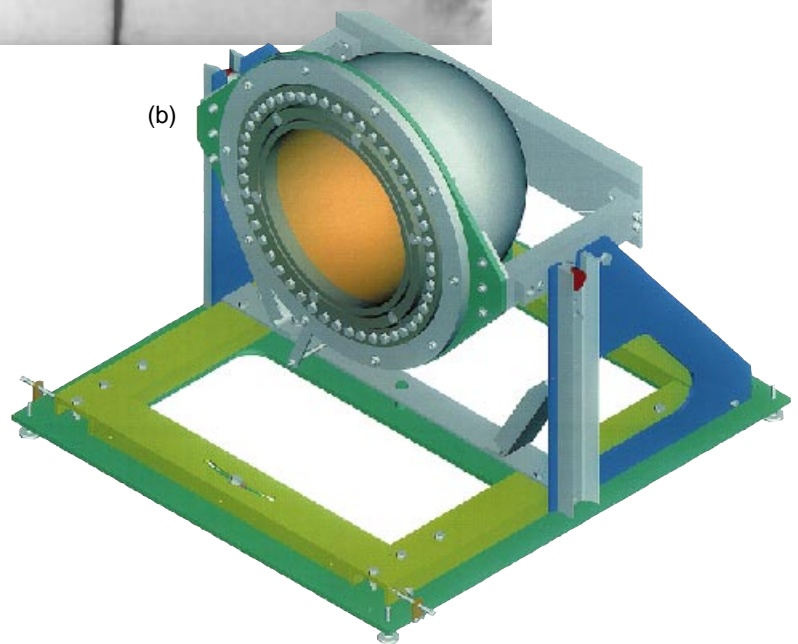
(a)

Figure 3. (a) Radiographs of resulting jet taken at three different times. (b) The shaped charge in its firing fixture prior to detonation.

(b)

photons of laser light reflected by the shaped charge to photoelectrons. These photoelectrons are accelerated by a high-voltage pulse onto a phosphor, where they are reconverted to photons that are then transmitted to the film. With exposure times of just 15 to 20 nanoseconds (up to ten times shorter than those of the framing camera) and a band-pass filter mounted on the camera to exclude extraneous light, the IC camera has supplied the first truly high-resolution images of the formation and early flight of a shaped-charge jet. The image in Figure 2(a) was taken with an IC camera and shows fine-scale features, including instabilities near the tip, the breakup of the material in the head, and even small ripples in the stem. Without the pulsed ruby laser illumination and the band-pass filter of the IC camera, this photograph would show only the hot gases encasing the jet as an extremely bright, luminous sheath.

The IC camera can record single frames at eight different times, stereo pairs of frames at four different times for three-dimensional photography, or combinations of each. The various frames may be focused on different portions of the jet, or they may be set to produce sequential photographs of the same portion of the jet.

In the high-resolution photographs, individual features on the jet surfaces as small as about 100 micrometers can easily be detected and followed as they evolve over time. When this information is combined with data from framing-camera images and x-ray shadowgraphs, Livermore researchers have at their disposal a detailed, verifiable record of the evolution of the jet.

Meeting the Challenge

Baum's team has found that by modifying the shape and design of the liner, they can control tip velocity and the mass

distribution in the jet to maximize penetration of a target. But the problem, of course, is that with continual changes in materials and construction methods, targets become increasingly difficult to penetrate. Therein lies the never-ending challenge.

—Katie Walter

A New Approach for Magnetically Levitating Trains—and Rockets

FOR the past two decades, prototype magnetically levitated (maglev) trains cruising at up to 400 kilometers per hour have pointed the way to the future in rail transport. Their compelling advantages include high speeds, little friction except aerodynamic drag, low energy consumption, and negligible air and noise pollution.
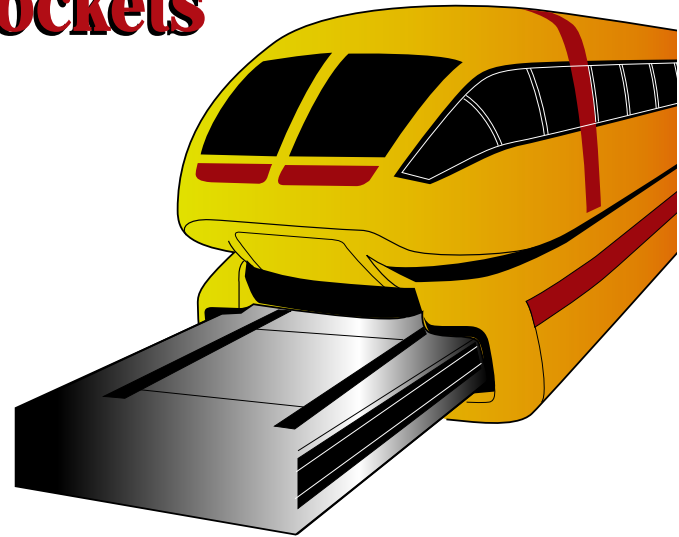
However, maglev trains also pose significant drawbacks in maintenance costs, mechanical and electronic complexity, and operational stability. Some maglev train cars, for example, employ superconducting coils to generate their magnetic field. These coils require expensive, cryogenic cooling systems. These maglev systems also require complicated feedback circuits to prevent disastrous instabilities in their high-speed operation.

Lawrence Livermore scientists have recently developed a new approach to magnetically levitating high-speed trains that is fundamentally much simpler in design and operation (requiring no superconducting coils or stability control circuits), potentially much less expensive, and more widely adaptable than other maglev systems. The new technology, called Inductrack, employs special arrays of permanent magnets that induce strong repulsive currents in a "track" made up of coils, pushing up on the cars and levitating them.

Totally Passive Technology

During the past two years, a Livermore team, headed by physicist Richard Post, has successfully demonstrated the Inductrack concept in test trials. The test runs demonstrated the system's totally passive nature, meaning that achieving levitation requires no control currents to maintain stability, and no externally supplied currents flowing in the tracks. Instead, only the motion of train cars above the track is needed to achieve stable levitation. The results have been so promising that NASA has awarded a three-year contract to the team to explore the concept as a way to more efficiently launch satellites into orbit.

Inductrack involves two main components: a special array of permanent, room-temperature magnets mounted on the vehicle and a track embedded with close-packed coils of insulated copper wire. The permanent magnets are arranged in configurations called Halbach arrays, named after Klaus Halbach, retired Lawrence Berkeley National Laboratory physicist. Originally conceived for particle accelerators, Halbach arrays concentrate the magnetic field on one side, while canceling it on the opposite side. When mounted on the bottom of a rail car, the arrays generate a magnetic field that induces currents in the track coils below the moving car, lifting the car by several centimeters and stably centering it.

When the train car is at rest (in a station), no levitation occurs, and the car is supported by auxiliary wheels. However, as soon as the train exceeds a transitional speed of 1 to 2 kilometers an hour (a slow walking speed), which is achieved by means of a low-energy auxiliary power source, the arrays induce sufficient currents in the track's inductive coils to levitate the train.

To test the Inductrack concept, Post, project engineer J. Ray Smith, and mechanical technician Bill Kent assembled a one-twentieth-scale model of linear track 20 meters long (Figure 1). The track contained some 1,000 rectangular inductive wire coils, each about 15 centimeters wide. Each coil was shorted at its ends to form a closed circuit but not otherwise connected to any electrical source. Along the sides of the track, they attached aluminum rails on which a 22-kilogram test cart could ride until the levitation transition velocity was exceeded (Figure 2). Finally, the team secured Halbach

arrays of permanent magnet bars to the test cart's underside for levitation and on the cart's sides for lateral stability.

The cart was then launched mechanically at the beginning of the track at speeds exceeding 10 meters per second. High-speed still and video cameras revealed that the cart was consistently stable while levitated, flying over nearly the entire track length before settling to rest on its wheels near the end of the track.

Post says the test results are consistent with a complete theoretical analysis of the Inductrack concept he performed with Livermore physicist Dmitri Ryutov. The theory predicts levitation forces of up to 50 metric tons per square meter of magnet array using modern permanent magnet materials such as neodymium–iron–boron. The theory also shows levitation of loads approaching 50 times the weight of the magnets, important for reducing the cost relative to maglev vehicles.

External Power Needed

Post notes that a power source is needed to accelerate the cart to its operating speed of 10 to 12 meters per second. The first section of the test track uses a set of electrically energized track coils—aided by a stretched bungee cord—to reach this speed. A full-scale train might use an electronic drive system, as found on experimental German trains, or even a jet turbine, as proposed by Inductrack engineer Smith. "Inductrack allows you the possibility of carrying all the power with you," emphasizes Post.

Even though the electromagnetic drag associated with Inductrack becomes small at high speeds, an auxiliary power source would also be needed to maintain the train's high speed against aerodynamic drag. The amount of power needed depends on the weight of the vehicle and its maximum speed. If the external drive power ever fails, or when the train arrives at a station, the train cars would simply coast to a stop, easing down on their auxiliary wheels. In this sense, Inductrack is a true fail-safe system.

Livermore is one of the few institutions to explore the uses of the Halbach array. Indeed, the Inductrack concept arose from Post's research on an electromechanical battery designed for superefficient cars and trucks (See April 1996 *S&TR*, "A New Look at an Old Idea," pp. 12–19). The Livermore battery uses circular Halbach arrays both to generate power and to achieve nearly frictionless magnetic bearings that minimize the loss of stored energy.

Figure 1. The 20 meters of scale-model track containing inductive wire coils used to test the Inductrack concept at Livermore. The test cart and electric drive circuit are in the foreground.

Figure 2. The test cart in motion levitated above the test track. The Halbach arrays can be seen beneath the cart and suspended from its sides. These arrays generate a magnetic field that induces, from the motion of the car, currents in the coils contained in the track, lifting and centering the cart above the track.

"We just unrolled the circular magnetic arrays from the electromechanical battery into a linear array on the car that seemed ideal for trains and other vehicles," he explains.

The Halbach array offers other benefits besides levitation. Because its magnetic fields cancel out above the magnets, there is no worry about magnetic fields affecting passengers' heart pacemakers. In contrast, passengers must be magnetically shielded on maglev trains employing superconducting coils.

The consulting company of Booz–Allen & Hamilton conducted a preliminary feasibility study of Inductrack and compared it to other maglev technologies. The study found that while an Inductrack system would cost more to build than conventional rail systems, it should be less expensive than maglev trains using superconducting coils. The study also found that Inductrack should be able to achieve speeds of 350 kilometers per hour and up and demonstrate lower energy costs, wheel and rail wear, propulsion maintenance, and noise levels.

Launching Rockets

Last October, negotiations were completed on a three-year contract with NASA to build a new Inductrack model at Lawrence Livermore to demonstrate the concept at speeds up to Mach 0.5 (170 meters per second). NASA is interested in maglev technology to help launch rockets at sharply reduced costs. As conceived, a track would use a reusable launcher to propel a rocket up a ramp to almost Mach 1 speeds before the rocket's main engines fire. According to Smith, the technology should be able to save about 30% of the weight of the launch vehicle. "Rocket engines are not fuel-efficient at low speed," he points out.

The Livermore team is designing a 150-meter-long track, to be built at the Laboratory site, on which a scaled launch cradle and rocket will be accelerated. Unlike the present track, the one for NASA will interleave powered drive coils with passive levitation coils to reach the required speeds. The team is partnered with computer scientists at Pennsylvania State University, who are developing an integrated design code that includes magnetics, aerodynamics, stresses, and control stability to assess full-scale systems.

Post believes Inductrack offers NASA the potential for a far less expensive technology for magnetic levitation launchers than approaches using superconducting coils. He and Smith note, however, that while the existing Inductrack model has demonstrated the principle of the concept, there are new issues to be addressed in launching rockets. Among these are high *g* forces, sustained speeds of Mach 0.5 or higher, the effects of fluctuating aerodynamic forces on the launching cradle and its payload, and aerodynamic and other issues associated with detachment and flight of rockets.

—*Arnie Heller*

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