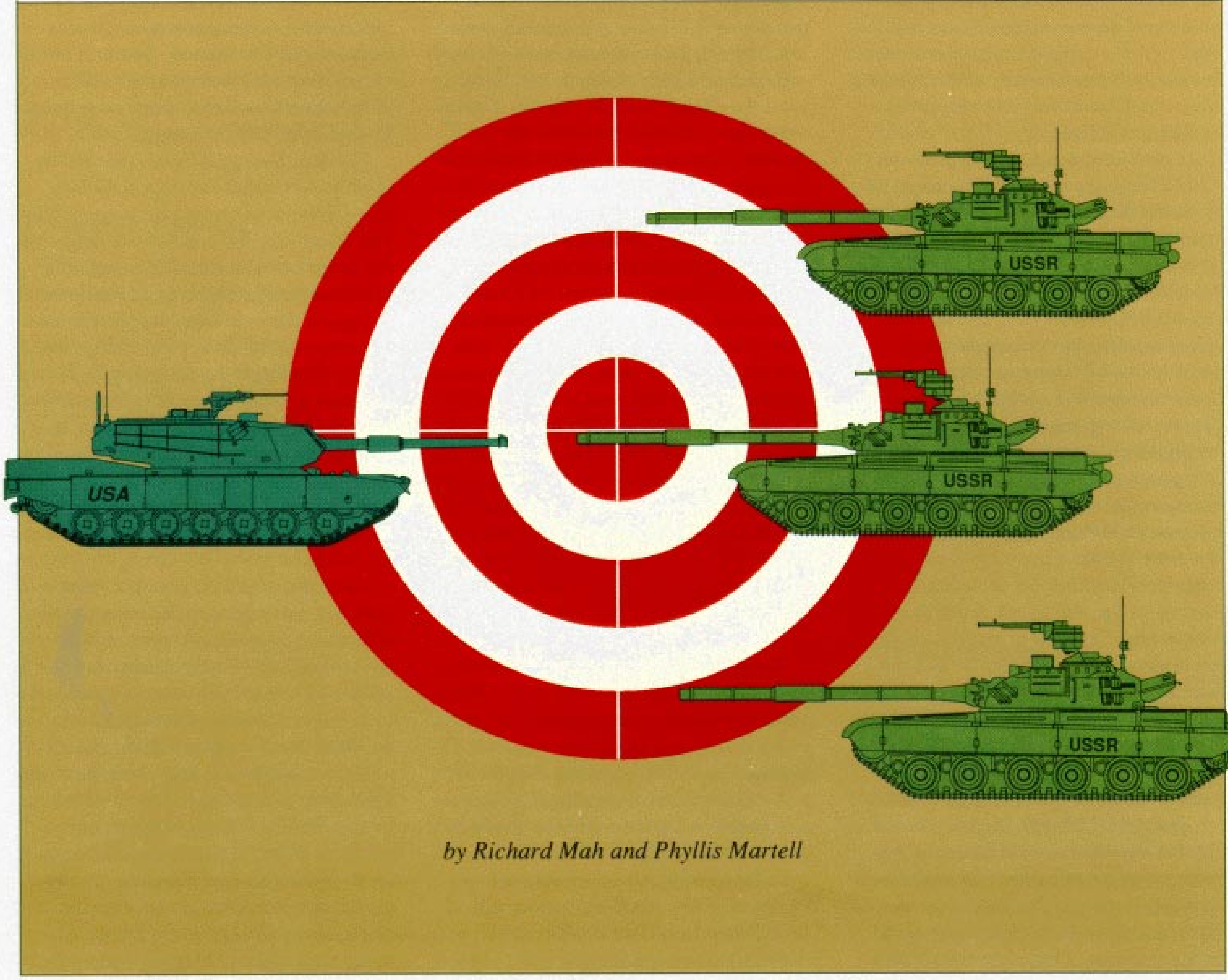
ATAC

and the Armor/Anti-Armor Program



by Richard Mah and Phyllis Martell

The Rand Corporation, E. I DuPont de Nemours, Honeywell, Inc., Battelle Washington Operation, Textron Defense Systems

A chief concern driving the current U.S. armor/anti-armor program is that the Soviets have a significant lead over the United States in tanks and antitank weapons (see “A Comment by General Starry”). Moreover, *simple* solutions in armor and anti-armor technology have already been implemented, so it may no longer be possible to find a “quick fix” that will catapult the conventional U.S. forces to a decisive lead over the Soviets. The problems are complex and the science sophisticated enough that we cannot depend on small, incremental improvements. We must base new solutions on a better *scientific* understanding of materials and their behavior under ballistic conditions.

As a result the national Armor/Anti-Armor Program, although spearheaded by DARPA (Defense Advanced Research Projects Agency), is also a collaborative effort with the U.S. Army, the U.S. Marine Corps, and 130 corporations, laboratories, and universities. A key element in this collaboration is the Advanced Technology Assessment Center created at Los Alamos to provide the strong scientific base needed for high-tech advances in armor and armor Penetrators. ATAC serves as both a testing center for new developments and a scientific resource that all participants can draw upon.

A major impetus for choosing Los Alamos as the Advanced Technology Assessment Center was history: there has always been a synergistic and intimate relationship between the Laboratory’s nuclear and conventional weapons technologies. In the early days of the Manhattan Project, ordnance experts came to Los Alamos to design essential components of the first nuclear devices. The overlap between the design of nuclear and conventional weapons that was established then, and which continues today, includes the hydrodynamics of high explosives, firing systems (detonators and electronics), materials properties (especially at high strain rates and extreme pressures), and computer modeling. Further, the precision required for nuclear ordnance has forced the Laboratory to explore these technologies at very detailed and precise levels.

Throughout the 1970s Los Alamos contributed to Department of Defense conventional munitions. For example, we developed a uranium alloy to serve as an armor-piercing round for the Air Force. The material proved so effective it became a standard for large-caliber Penetrators. We also collaborated with industry and Navy laboratories to solve a propellant safety problem that threatened the Trident system. This last effort led to the joint development—by Los Alamos, Lawrence Livermore National Laboratory, and the Air Force Rocket Propulsion Laboratory-of a methodology for testing the safety of solid rocket propellant. One of our most notable contributions was the *long standoff penetrator,* a shaped-charge, chemical-energy weapon that was tested in 1979 and shown to penetrate more deeply into armor than any other such weapon. Interest in the design of this penetrator led to more extensive Los Alamos interactions with Department of Defense munitions researchers and, ultimately, to the choice of Los Alamos as ATAC.

Armor/Anti-Armor Program Goals

The long-term goals of the national Armor/Anti-Armor Program are to develop a broad base of expertise in private industry and make that expertise available to the U.S. Armed Forces. On a short-term basis the national program also hopes to increase the rate at which we modernize armor and anti-armor systems until the U.S. can outperform the Soviet Union in the development of several key technologies. The strategy devised to accomplish both goals is to challenge industry in the key technologies by making the research, development, test, and evaluation stages of the national program highly competitive.

The strategy has been implemented by breaking the core of the Armor/Anti-Armor Program into three major elements: the Blue Teams, the Red Design Bureau, and ATAC. The Blue Teams consist of contractors who are developing armor and antitank weapons. These contractors are large industrial corporations that have enlisted universities, national laboratories, and other corporations as subcontractors to help with their competitive efforts. The first phase of the program involves about 130 major contractors selected from an original field of over 400 companies.

The Red Design Bureau—headed by Battelle Memorial Institute in Columbus, Ohio was created to design a “Soviet threat” for the competitive stages of the program. The threat is based on an independent evaluation of available intelligence data. In other words, the Bureau tries to “think Soviet, ” design what the Soviets might be designing, and then fabricate actual prototypes. These futuristic Soviet armors and Penetrators are used to test and assess the Blue Team hardware. Members of the Blue Teams do not learn what the threat will be until about a month before competitive testing.

The roles of ATAC are, first, to stimulate the entire process by transferring technology from Los Alamos to industry and, second, for the Laboratory to serve as a neutral referee in the competitive stages. Specifically, ATAC helps the Blue Team members develop better products, and then it tests those products against the threat created by the Red Design Bureau. Much of the help provided by ATAC comes from two major areas of Los Alamos research: materials science (see “Armor/Anti-Armor—Materials by Design”) and computational codes (see “Modeling Armor Pen-

General Research Corporation, Nuclear Metals, Inc., Aerojet Ordnance Co., AAI Corporation, FMC Corporation, Physics International Company

etration"). ATAC is also responsible for ensuring that testing of Blue Team products is performed and evaluated accurately, thoroughly, and without bias. Our evaluations include recommendations for future funding of promising technologies.

ATAC'S effectiveness in the Armor/Anti-Armor Program requires that Los Alamos be at the technical forefront of armor and anti-armor research. Thus ATAC invests a significant portion of its budget in research on materials science and technology, development of diagnostic techniques, and computational research. In addition, Los Alamos has contracted a number of consultants and universities for help in disciplines outside the expertise of Los Alamos scientists.

A Scientific Challenge

The basic challenge in armor/anti-armor research and development is to *understand each problem from sound physical principles and the appropriate materials properties.* For example, our thinking about the usefulness of ceramics as armor material changed drastically with an increase in our understanding of ceramic material properties and how ceramics react physically to ballistic impact.

One of the most efficient ways for armor to defeat a projectile is to turn most of the kinetic energy back into destruction of the projectile itself, say by fracture or plastic flow in the penetrator. Ceramics were considered possible as armor material because they generally have high compressive strength and are lightweight, two qualities desirable for mobile weapons systems that need tough, light armor. Unfortunately, ceramics also tend to be brittle and break up easily on impact, which, it was thought, would undermine the material's ability to destroy the penetrator. When ceramic materials were tested, however, they appeared much more efficient than expected. In truth, no one understood how the armor worked.

Eventually it was proposed that the breakup created a mass of hard, abrasive ceramic chips that eroded the penetrator. Detailed computational and materials research at both Los Alamos and Livermore confirmed this hypothesis and made us realize how to turn the apparent disadvantage to our favor. The goal was then to keep fractured ceramic in front of the penetrator as long as possible, causing the rod to erode as it forced its way through the rubble. As a result, how the material was packaged became as important as its strength and fracture characteristics.

Only by examining defeat mechanisms in this detailed way can scientists optimize both the material characteristics (abrasive chips) and product design (how to confine those chips) to enhance the desired effects. (See both "Armor/Anti-Armor-Materials by Design" and "Studying Ceramic Armor with PHERMEX" for a fuller discussion of ceramic armors.)

The same challenge of' understanding the physics of the ballistic event, the materials involved, and the effect of product design is true for Penetrators. An example is the metal liner used in chemical-energy weapons. The detonation of a shaped charge moves this liner at the target in such a way that the material transforms into a high-velocity jet of solid stretching material. To be effective, the liner must have the proper combination of strength and ductility to allow it to stretch without breaking.

If one is to achieve a desired liner performance, criteria—such as the material density, the tip velocity, and the coherency of the jet—must first be determined. Then the key elements necessary to those criteria must be identified. For instance, work at Los Alamos has shown that selection of liner material, design of the charge, and the crystalline microstructure of the liner are critically important. Additionally, we have found that a specific "heat and beat" fabrication process for each material has to be followed to achieve the preferred crystalline microstructure. We had to explore a variety of these processes to select the correct one—an expensive, time-consuming task if done solely on an experimental basis. We hope to shorten the task considerably by using a computer model to predict liner performance based upon various crystalline microstructure. We will make this information and the modeling code available to others, including Blue Team contractors. In fact, industry has been briefed on the preliminary work.

We are hoping that the same process evolves for kinetic-energy Penetrators, which several Blue Team contractors have undertaken to explore. At present, the idea that dominates development of kinetic-energy Penetrators is simply that the heavier the penetrator and the faster it hits the target, the better. However, Blue Team contractors are asking themselves several questions: What mechanical properties should be considered? Does fracture toughness give the penetrator its ultimate strength? What effect does chemical composition have on this strength? In other words, a better understanding of the physics of high-velocity impact needs to be acquired. This is the type of challenge facing the Blue Team.

Current Research

Further advances in the development of the chemical-energy warhead is a tactically urgent problem that the Armor/Anti-Armor Program is currently tackling with much vigor. Before reactive and spaced armors were introduced, chemical-energy weapons had a number of clear-cut advantages. For instance, the chemical-energy penetrator is better at penetrating steel armor than

continued on page 56

A *Comment* by General Starry

"We are behind the Soviets in both armor and bullets. That simple declarative sentence is what makes the ratification of the Intermediate-range Nuclear Force (INF) treaty a provocative action. It is the raison d'etre for the new national interest in armor and anti-armor technologies. And it was the principal finding of the 1985 Defense Science Board Task Force on Armor/Anti-Armor, of which I was the chairman.

"Our Task Force study reported that, in armor and anti-armor systems, the U.S. has been behind the Soviets for perhaps fifteen to twenty years, and we are falling further behind at an alarming rate (see Figure). Back in 1985, we considered the problem as one 'approaching a matter of national urgency.' Today we have crossed the threshold; the situation is now a matter for urgent national priority.

"The problem is not a lack of technology or intelligence data. Scientific journals and other open literature collectively provide a fairly substantial body of data from which we can determine, at least by inference, what they are doing in research and development.

"However, over time, we find information concerning a given technology declining in volume or even disappearing from their literature, Does this mean that the Soviets have given up on a technology? The U.S. has a tendency to believe so. That may be true, but it is equally possible that they have moved the technology into full-scale engineering development. Eight to ten years may pass. Then, all too frequently, we identify what we would call a new weapon system on a test track or, in some cases, being issued to the troops—a system that fields the so-called disappeared technology.

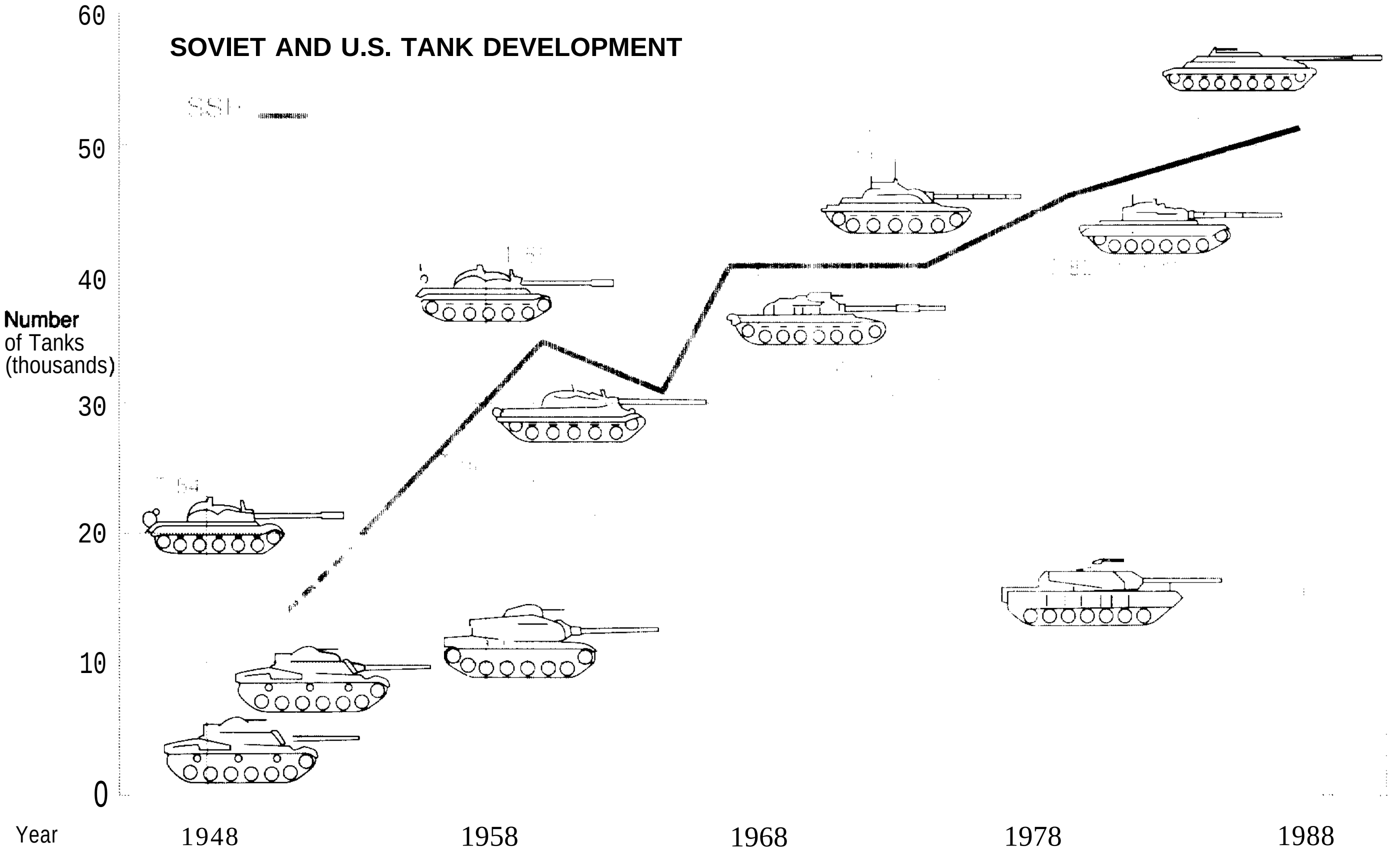
"The Task Force called this decline of information during full-scale engineering *the Bathtub of Ignorance,* Historically, it has taken us at least five years to catch up and frequently as long as fifteen years to apply the same technology in our fielded systems.

"This is not an indictment of our intelligence system. We do gather sufficient information on which to make fairly reliable estimates. In fact, three years ago we had the intelligence community make some estimates of what was in the 'bathtub;' to no one's surprise, those developments are now beginning to appear.

"The flaw, instead, is in our decision-making process. Our system reacts positively only when confronted with hard evidence—a photograph of fielded equipment—and negatively to an intelligence community 'bathtub' projection. No one in Washington is willing to make a decision until shown a picture of a fielded system incorporating new technology; then there will be all sorts of doomsday and 'how could this have happened' reactions.

"So the first problem our country has is how we look at the threat. The second problem is one of technology fielding. We are fighting against a natural tendency of laboratory scientists-even at places like Los Alamos—to keep the technology at the workbench too long. Of course, they want to keep improving the capabilities, But if you allow the scientists more and more time and funds, you may end up with a wait of five to ten years, an expenditure of millions or billions of dollars, and only a marginal improvement in performance, In other words, a laboratory has no incentive to get the technology out.

"It is vital to have a decision-making mechanism to drive the technology off the workbench and into the field. The Soviets have such a mechanism: the five-year planning process. Relentlessly, every five years the Soviets transfer technology from the bench to the field. We have-no similar system. In fact, the Task Force examined thirty of our technology developments and found at least



SOVIET AND U.S. TANK DEVELOPMENT

* Classified or unknown

U.S./SOVIET	T-54	M-47	M-48	M-60	T-55	T-62	T-64	T-72	M-1	T-80	FST-I
Crew	4	5	4	4	4	**4**	**3**	**3**	4	**3**	•
Combat Weight (metric ton)	**36**	46	45	53	**36**	**37**	35	41	57	42	*
Power/Weight Ratio (horsepower/rnetric ton)	14.4	17.5	18.0	14.2	**16.1**	**14.5**	**18.4**	**19**	26.2	higher	*
Maximum Road Speed (kilometer/hour)	48’	48	42	48	50	50	80	60	66	90	*
Main Gun Diameter (millimeter)	100	90	90	105	100	115	125	125	105	125	*
Turret Front Armor Thickness (millimeters)	203	115	110	*	203	242	*	280	'	*	*

Soviet tank development outpaces that of the U.S. both in total numbers and in the introduction of modern technology. The Soviets regard the tank as the primary element of their ground combat power, and Soviet military theory emphaslzes the Importance of the tank in the combined-arms team. As a result, the Soviets commit a major portion of their resources to their tank industry, achieving an Integrated, evolutionary program of tank development that produces thousands of main battle tanks each year. Long-term improvement can be seen In all three Soviet armor subsystems-firepower, protection, and mobility. Modern tanks (T-64, T-72, and 1-60) now make up approximately forty per cent of the Soviet force in the field. (The information for this figure was compiled by the International Technology Division of the Los Alamos National Laboratory.)

a dozen that had been funded at entry levels of developments for twelve to fifteen years. I believe this situation illustrates that while we may be ahead of the Soviets technically, more and more the advantage may only be on the laboratory bench.

"The third problem we identified is our programming system—this is a function of the way we build budgets. For most programs, except for a few R&D programs, the budget is a one-year cycle. That means each year we have to renegotiate the budget, and priorities may be different. Some people call that 'an up and down' budget; I describe it as a zigzag process. It takes time and money, most of which is wasted as you zig and zag. Connected to the one-year budget problem is the fact we have no orderly system for block modifying our big weapon systems. Historically, the Soviets have been able to modernize a whole fleet with new technology every ten years; because of our programming system, it takes twenty to twenty-five years. That is the basic, fundamental problem.

"The final problem identified by the Task Force was the lack of an effective acquisition management system. Activities were going on all over the country in armor and anti-armor with no one in charge. No one was tasked with the mission of bringing it all together and implementing it. Let me give you an example of an effective acquisition system. In Israel, a man named Israel Tal—a retired Major General and a great hero of the Israeli Armed Forces—is the Deputy Minister of Defense for Armor Vehicle Programs and the czar of tank and other vehicle development. His establishment literally tests something every week, immediately looks at the results, and decides what to test the following week. Thus, they are forever narrowing their options, and, as a result, field new technology on new vehicles at a rate we simply cannot match. An additional benefit is that General Tal—who is driving the program to completion—was not only an ultimate user in the past, but he is also still closely affiliated with the Israeli Armor Corps. We need that tight symbiotic relationship as well.

"The Task Force concluded that, historically, we have always been in a catch-up mode. Yet, by the time we supposedly catch up, momentum on the other side has put the threat ahead of us once more. Moreover, we are unable to achieve and sustain a modernization rate that can match or better that of the Soviets. The end result is that the Soviets are outmodernizing us at a rate of about four to one. For example, every year they modernize a force the size of the total U.S. heavy force, and every two years they modernize a force the size of the total NATO heavy force. Our modernization rate is dramatically less robust.

"These conclusions led the Task Force to make several recommendations to the Secretary of Defense. One of our strongest was to ask DARPA to set up a program that would address the problems. That was the origin of the national Armor/Anti-Armor Program—a program in which the Advanced Technology Assessment Center (ATAC) at Los Alamos National Laboratory plays a significant role."

—Donn A. Starry, General of the U.S. Army (retired) and Executive Vice President of Ford Aerospace Corporation

continued from page 53

THE TOW MISSILE

Fig. 1. A soldier, almost completely hidden by his ground launcher, fires a Hughes TOW missile during training. As the missile flies toward the target, the soldier tracks it optically, guiding it with signals transmitted through the wires seen spiralling out of the back of the missile.

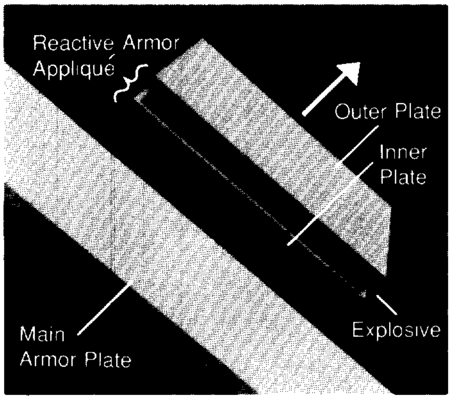
gun-fired kinetic-energy penetrators by a factor of at least two to one. Also, the destructiveness of the chemical-energy penetrator is not dependent on the energy of the delivery system because the penetrator is formed and driven by explosives in the warhead. No barrel is required to direct the penetrator, and no particular velocity needs to be attained to make the weapon effective. Unlike kinetic-energy penetrators, chemical-energy weapons are light enough to be carried by a soldier or transported by unmechanized forces. Finally, the deployment of highly accurate weapons in the early 1970s—such as the TOW missile, which is tube launched, optically tracked, and wire guided (Fig. 1)—nearly doubled the effective engagement range of chemical-energy penetrators.

Aluminum Company of America (ALCOA), General Motors Delco Systems Operation, A.R.A.P. Division of California Research and Technology

But the situation started to reverse itself in the mid-to-late 1970s when the advent of spaced armor, then ceramic laminate armor, and finally reactive armor reduced the effectiveness of chemical-energy weapons. Today the combination of spaced or ceramic armor and reactive appliques has probably made every fielded system using a chemical-energy warhead obsolete.

Reactive armor-used first by the Israelis in the 1970s and now estimated to be on half of the Soviet tanks—is a formidable challenge (Fig. 2). It was developed primarily as a countermeasure for chemical-energy weapons and consists of a trilayered sandwich of metal, high explosive, and metal. Tile-like boxes of reactive armor are simply bolted to vulnerable areas of a tank outside its existing armored shell.

Because of the ability of reactive armor to destroy an incoming jet, some people in the weapons community fear that fielded chemical-energy warheads are now obsolete. However, preliminary tests of some new chemical-energy warheads developed by Blue Team contractors show promising results. Significant improvements in performance seem attainable with existing technology. Unfortunately, we cannot give more details on these developments due to the proprietary nature of the new designs.



REACTIVE ARMOR

Fig. 2. Reactive armor typically has a layer of high explosive sandwiched between two layers of armor plate. When a high-energy jet collides with the armor, the explosive detonates, pushing the plates into the path of the jet to deflect or deform it, thereby protecting the inner layer of armor. Ideally, the reactive armor plate will be moving at an angle to the path of the jet, forcing it to drill a slot rather than a hole through the plate and giving the plate a larger effective thickness.

We can, however, talk about one promising concept—tandem chemical-energy warheads (Fig. 3). In these weapons a small charge at the front of the warhead fires to activate the tank's reactive armor. A time delay allows the reactive-armor plates to move out of the way, then a large shaped charge further back in the warhead fires a metal jet to defeat the base armor. Weight reduction technologies, various time delays between the firing of the two charges, and innovative designs and materials for the shaped-charge liners are currently being developed. Blast shields between the precursor and the main charge are being optimized, and the most effective *stand-off distance-* the distance to the shaped charge at the instant of its detonation—is being determined. Tandem chemical-energy warheads seem likely to play an important role in the defeat of reactive armor.

The national Armor/Anti-Armor Program has also taken up the challenges of new composite materials and advanced processing techniques. To achieve the low weight and elevated mechanical properties needed for armors, the ideal material may actually be a composite of ceramic and high-strength reinforcements. Ceramics possess low density, high hardness, dilatancy (the tendency to expand when fractured), and high shear strength—all good properties for armor-but they lack fracture toughness, the ability to resist crack propagation, which for some purposes, such as multiple-hit resistance, may be important. To improve fracture toughness without sacrificing the other properties, we are investigating the use of single-crystal whiskers or platelets as a reinforcement in ceramics. Tailoring material properties for specific applications is one of the challenges of armor development.

Interface With Industry

How is Los Alamos helping industry to meet the challenges of the Armor/Anti-Armor Program'? A recent incident illustrates how ATAC's presence at Los Alamos allows the program to tap the Laboratory's experience and developed technology. Los Alamos has always performed nondestructive inspections of every nuclear weapon system tested. It was thus only natural to perform the same tests on the chemical-energy warheads sent to us by Blue Team contractors. The evaluations revealed heretofore undetected cracks and voids in some of the warheads that could have affected performance. We informed the contractors of the problems so they could make substitutions, thus ensuring that all participants had a fair chance in the competition.

ATAC also provides direct help in solving contractor's problems. Our program managers, test directors, hydrocode developers, and materials scientists deal on a one-to-one basis with our industrial counterparts. For example, last summer we worked with the company that produces the Joint Services hypervelocity missile to help solve a control problem. The missile consists of a large kinetic-energy penetrator mounted in the missile's warhead. Although the warhead is very heavy, the missile is long range and able to move fast— 1.7 kilometers per second. Unfortunately, the aluminum tins on the missile-critical to its stability and control-melted during flight. We eventually solved the problem by suggesting

A TANDEM WARHEAD

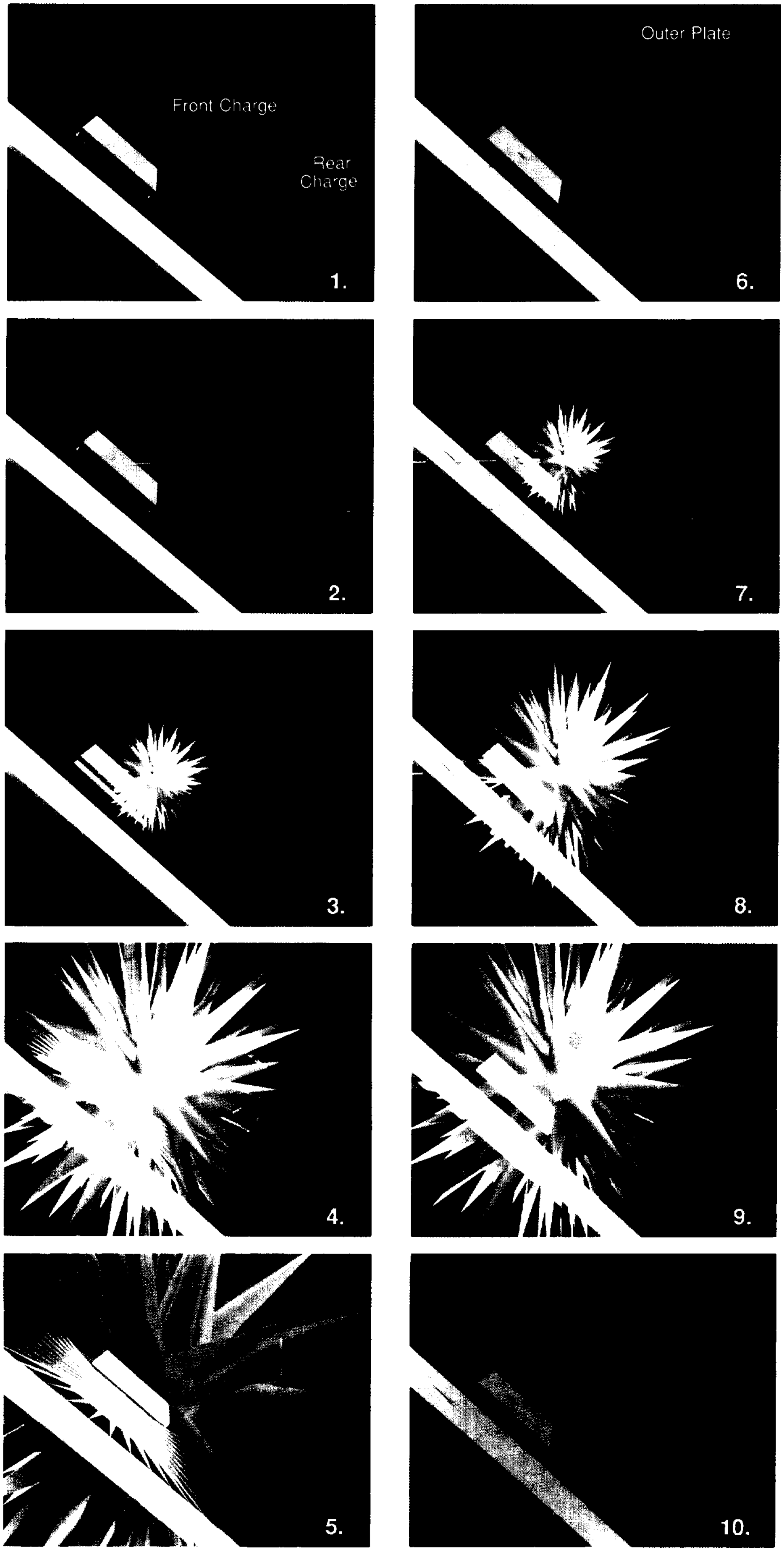


Fig. 3. One concept for defeating reactive armor is to use a chemical-energy warhead with two explosive charges rather than one. As the warhead approaches the armor (1 through 3) the small explosive charge at the front of the warhead is detonated. The resulting impact activates the explosive in the reactive armor (4 through 6), causing the plates of armor to be blown away. Later, the large explosive charge at the rear of the warhead fires (7). However, the angle of the armor and the gap between the warhead's initial and final charges causes the plates to miss the penetrating jet formed by the detonation of this second charge.

California Research & Technology, Kaman Sciences, Inc., Lawrence Livermore National Laboratory, Radkowski Associates, General Dynamics

both a particular ceramic coating and an application technique for the coating.

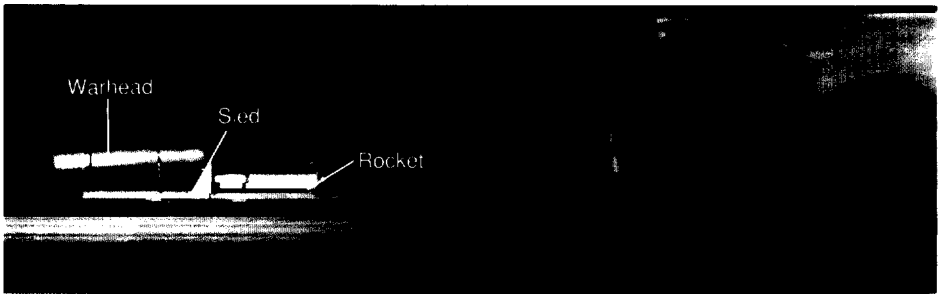
ATAC Facilities

ATAC, in its role of testing and evaluating the competing antitank systems and armors, uses Laboratory expertise, technologies, and capabilities. For example, we are testing chemical-energy warheads using the 1000-foot monorail rocket sled track at Los Alamos (Fig. 4). The sled can reach Mach-1 speeds, and the track can be extended to 2000 feet if higher speeds become necessary. The sled track is very useful for carrying out realistic tests of tandem-warhead designs. Most tandem designs have a significant time delay between firing the first and second warheads, during which time the second warhead moves considerably. The rocket sled can be used to test the effect of missile motion under precisely controlled conditions.

We are also building a new intense flash x-ray machine next to the sled track, This machine should allow armor and anti-armor developers to "see" the penetration process through eight inches of steel (Fig. 5). The source in this system will operate at 8 to 10 mega-electron-volts (MeV) and generate an x-ray dose greater than 500 roentgens at 1 meter. This device will easily track both kinetic-energy Penetrators and chemical-energy jets well inside the targets.

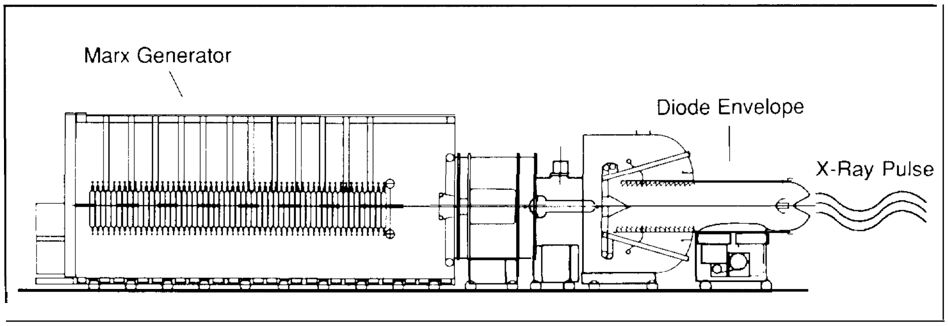
ROCKET SLED

Fig. 4. A chemical-energy warhead is shown being tested on the rocket sled at Los Alamos. Mounted on a 1000-foot monorail, the sled can reach Mach-1 speeds and allows scientists to test warheads under controlled but realistic conditions.



FLASH X-RAY MACHINE

Fig. 5. A flash x-ray machine being constructed at Los Alamos capable of "viewing" ballistic events through eight inches of steel. When the 8 to 10 million electron volts of energy stored in the Marx generator are released into the diode envelope, electrons accelerated from the cathode to the anode will generate an x-ray fluence greater than 500 roentgens 1 meter from the end of the diode.

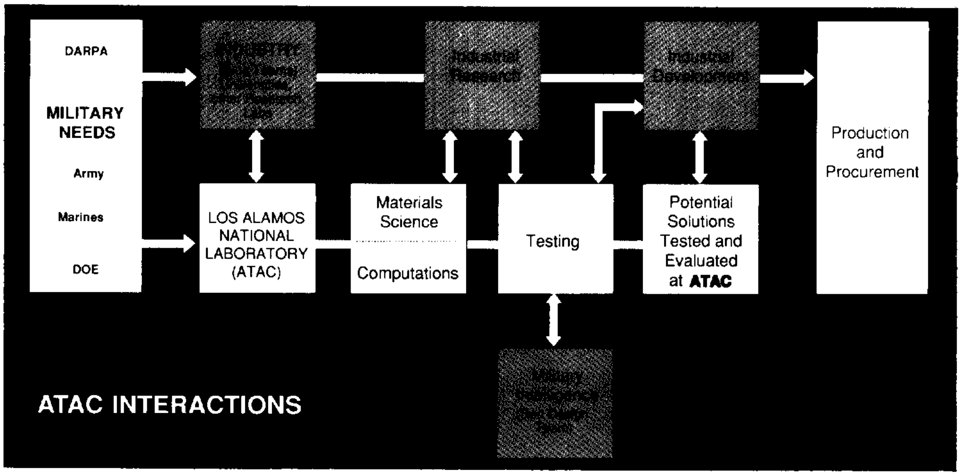


Los Alamos also designed and helped develop a state-of-the-art test range in Socorro, New Mexico, at the Terminal Effects Research and Analysis (TERA) branch of the New Mexico Institute of Mining and Technology. The range occupies 1 square mile and features a highly instrumented target area that follows the incoming trajectory and target response *optically.* A continuous record of the test is provided by an advanced video system that operates at speeds up to 2000 frames per second. All data are logged and processed automatically by computers, which allows Los Alamos personnel to control the firing times of munitions and to measure time and space information relative to the arrival of the devices. Technical calculations can be done directly from the video. There is also a four-camera. single-image system with a ten-nanosecond shutter speed. The multiple cameras, combined with electronic imaging, permit Los Alamos personnel to locate the position of munitions within the target area and not interfere with the munitions control and guidance equipment. ATAC built the range at TERA because sufficient land was not available at Los Alamos for safe firing of full-size live missiles and projectiles.

A variety of other diagnostic capabilities are available for gathering the maximum data from each test performed at Los Alamos, These include four portable 2-MeV x-ray systems, twelve 450-keV flash x-ray machines. five rotating-mirror streak cameras with writing speeds of 20 millimeters per microsecond. four image-intensifier cameras with X)-nanosecond shutter times, a laser velocitmeter and a microwave

General Electric Company, Ordnance Systems Division, Science & Technology Associates, New Mexico Institute of Mining & Technology

Fig. 6. One of the goals of the national Armor/Anti-Armor program is to establish a useful flow of information between the military, industry, and various research institutions. The interactions of ATAC with this network continue beyond the research phase into the testing, development, and perhaps even production phases of the weapon systems.



velocimeter to record transit velocities, time-interval meters with nanosecond resolution, 200-megahertz analog-to-digital signal converters, and a wide range of more conventional instrumentation, We also can use PHERMEX, a 30-MeV flash x-ray machine, and ECTOR, a 3-MeV machine. Both of the machines have access to impressive digital-enhancement capabilities for flash radiographs, and they allow us to determine the internal structure of anti-armor and armor devices at the time of impact (see “Studying Ceramic Armor with PHERMEX”),

An Evolving Process

At ATAC we can see a new process evolving among industry. the military, and the Laboratory in which a natural interplay of needs, research, testing, prototyping, evaluating, developing, and procuring guides the development of armor and anti-armor systems (Fig. 6). To illustrate how the process works, consider the case of ceramic-filled polymer armor (described in “Armor/Anti-Armor-Materials by Design”). When the military told the Laboratory about the need for a less expensive ceramic armor, our materials scientists tested various ideas and developed a process for fabricating a less expensive but equally effective ceramic armor. We then initiated transfer of the technological concepts to industry, and Allied Signal used the ideas to develop their own armor package. Allied Signal is now busy producing prototypes of the armor, which they will submit for testing and evaluation at ATAC. If that armor is successful in the competition, it will eventually become a new product available for military use.

The true value of the national Armor/Anti-Armor Program may not lie in a simple leapfrogging of Soviet armor and bullets by U.S. technology. Rather it may lie in the way this uniquely structured program has opened fresh interactions between our nation’s military, industries, laboratories. and universities that will allow us to constantly maintain an edge over the Soviets. ■

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Studying Ceramic Armor with PHERMEX

by Ed Cort

The ballistic impact of penetrator against armor is a brief moment of violence and shock hidden in a confusion of smoke and debris (Fig. 1,). If we are to learn what material properties are relevant to the outcome, we must pierce the veil and freeze in place the key aspects of this event. Large x-ray machines are ideally suited to this task. A short flash of intense x-radiation can penetrate the debris and armor and etch an instantaneous image of deformation and material flow.

We are currently using an x-ray machine called PHERMEX (Fig. 2) to study the internal structure of ceramic armor during impact with both penetrating jets from chemical-energy weapons and long-rod kinetic-energy penetrators. The machine uses a 30-MeV high-current linear accelerator to generate very intense but short-duration bursts of x rays from a thin tungsten target. Although built in the early 1960s, PHERMEX is still unequaled at producing high-resolution radiographs of large, fast. objects. We are particularly interested in using PHERMEX to study ceramic armor because the mechanisms by which ceramic armor can defeat a penetrator differ in certain key ways from the defeat mechanisms of more traditional armors. We have only recently begun to

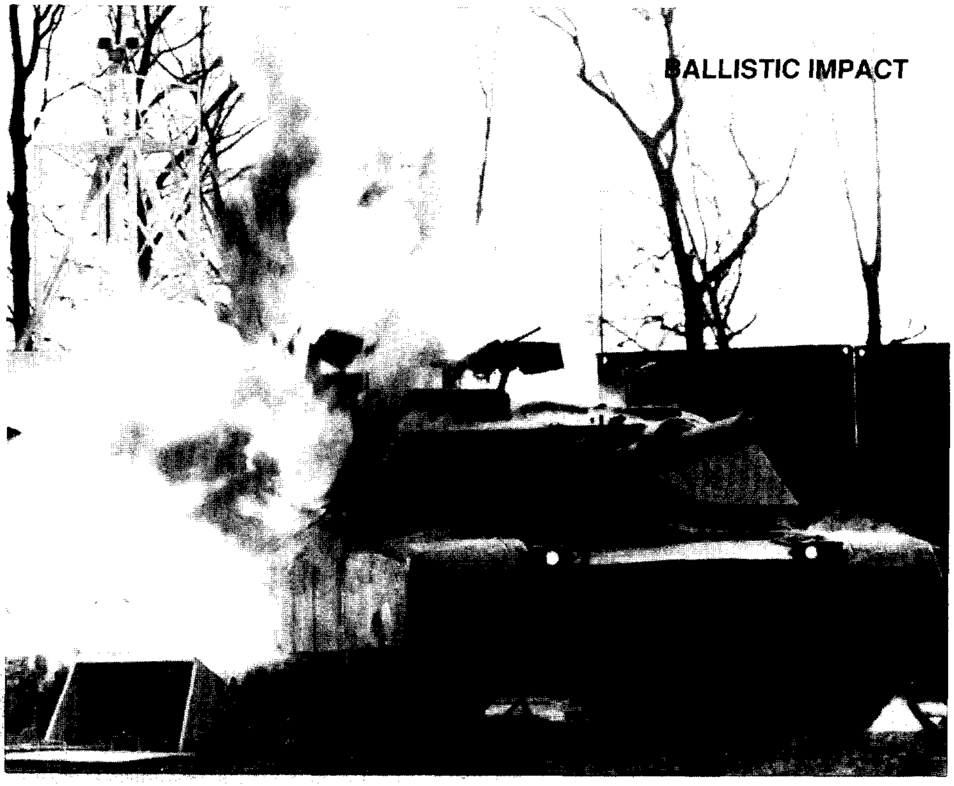


Fig. 1, Live fire test of the M1A1 Abrams tank at Aberdeen Proving Ground. (Photograph taken by U.S. Army Combat Systems Teat Activity and provided to Los Alamos by the U.S. Army Ballistic Research Laboratory.)

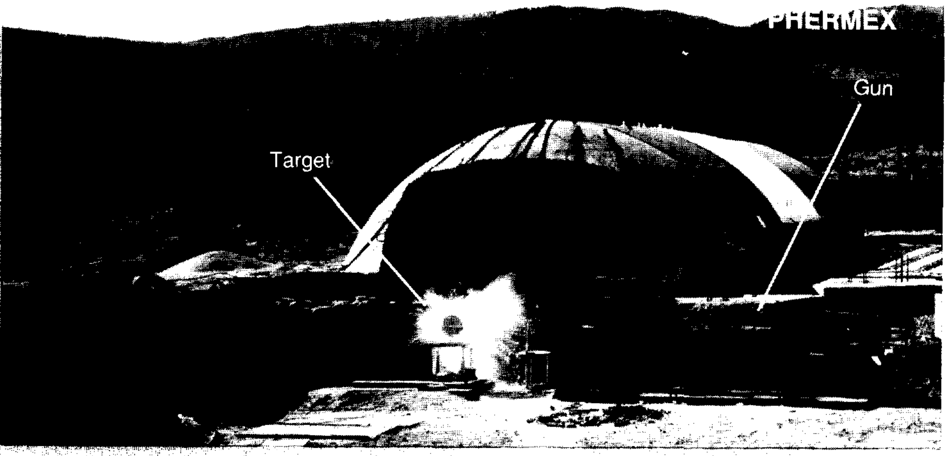


Fig. 2. A flash x-ray machine (in the building behind the target) is currently being used to produce high-resolution radiographs (see Fig. 4) of the ballistic interaction of ceramic targets with long-rod penetrators (fired from the gun at the right).

understand what those differences are.

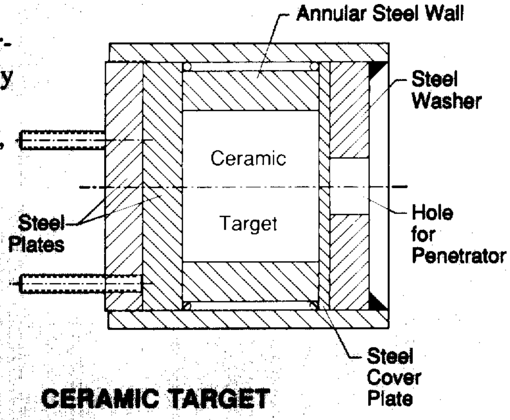


Fig. 3. The targets used to study the response of ceramic to impact by a penetrator rod were designed to keep the ceramic confined during the event. The penetrator rod enters the front of the target through the hole in a steel washer and then strikes a hardened steel cover plate. At a predetermined time after impact, the PHERMEX is pulsed.

The long-rod penetrator pierces a target, whether ceramic or otherwise, by depositing large amounts of kinetic energy in a concentrated region," The rod, which may be idealized as a right circular cylinder with a length typically ten or more times greater than its diameter, is intended to strike the target "end on." Any yaw (deviation of the rod's axis from its direction of flight) of more than a few degrees can adversely affect penetration. When the target thickness is greater than a few penetrator diameters—usually the case for problems of interest—penetration is a complex process in which a cavity forms in the target material and the impacting end of the penetrator erodes away. If the incoming rod is yawed, the penetrator may bend or break and lose much of its effectiveness. Heavy armor that is intended to defeat long-rod penetrators is nearly always sloped with respect to the anticipated flight line of the projectile to create oblique impact conditions. Modem armor also tries to induce yaw on impact with reactive sandwiches, tipping plates, and other devices. The combination of obliquity and yaw presents difficult modeling and experimental challenges.

Even non-yawed impact of long-rod penetrators is not well understood when the target is *confined* ceramic armor. One aspect of this problem—the complex way in which the confinement package itself interacts with the ceramic during impact—has not always been well controlled experimentally in the past. We have built targets that are so constrained by steel that confinement is relatively constant from shot to shot and penetration depends on ceramic behavior entirely. We are able to study such thick targets by capitalizing on the penetrating ability of the high-energy x rays of PHERMEX. Although the targets (Fig. 3) do not represent a realistic armor design, their response to penetrator impact is more reproducible and predictable, and the ceramic's behavior is relevant to the general problem.

To obtain radiographs of a rod or a jet penetrating the ceramic, we pulse the PHERMEX once during each impact. These pictures reveal the residual length of eroded penetrator, the depth and rate of penetration, the material's residual velocity, and whether or not the penetrator is, say, mushroomed at the front, bent, yawed, or broken. The radiographs also reveal the distribution of debris, the shape of the crater, and the presence of large cracks or distortions in the target. However, the radiograph's limits of resolution coupled with strong confinement pressure from the target holder prevent the image of the fracture in the ceramic from being well defined.

We use targets that are thick enough to stop the penetrators in the ceramic and make a radiograph of the target after each shot to show the final penetration depth and the length of any remaining rod or jet material. A sequence of four to six nominally identical shots produces a time-resolved penetration history for one ceramic material and one set of engagement conditions (velocity, obliquity, and yaw) in one plane. In future tests, we hope to flash PHERMEX several times during impact and record a series of dynamic radiographs electronically.

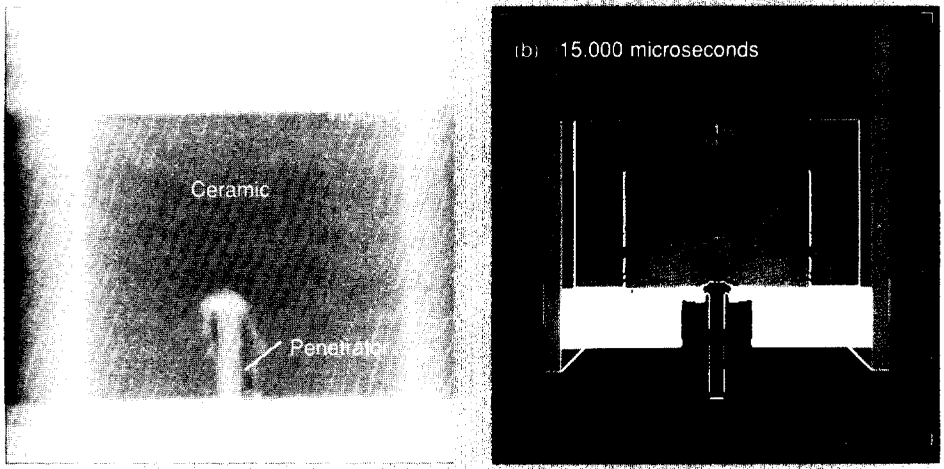
Our current test series ranges over three ceramic materials (boron carbide, aluminum oxide, and titanium diboride), two impact velocities, two obliquities, a number of confinement geometries, and both kinetic-energy rods and jets from chemical-energy weapons. We also look at the flight characteristics of the penetrator (velocity, yaw in two orthogonal planes, rate of change of yaw, and fiducial time at impact).

We are modeling the tests with existing hydrocode models (see "Modeling Armor Penetration"). The code predicts that because the ceramic is relatively incompressible, even when fractured, and because there is no free volume for the rubble to expand into except the penetration hole itself, the ceramic defeats the penetrator. Although the predictions of ‘the model are reasonably close to actual events (Fig. 4), our material model for the ceramic, at the moment, is based more on experimental data from prior tests rather than on principles of physics. Consequently, if the rod's velocity, say, were to change significantly, we would not be able to extrapolate with confidence.

At the end of our current series of approximately thirty shots, an advisory panel of experts ‘will review the tests and help interpret the data. However, preliminary results confirm that dilatancy (the tendency of the fractured ceramic to expand) is an important gen@# feature for the defeat of jets fired from chemical-energy weapons. In this mechanism the ceramic rubble refills the impact hole, constantly'fmcing the jet to penetrate new material, and, as the

CERAMIC PENETRATION

Fig. 4. (a) A PHERMEX radiograph of a tungsten-alloy penetrator colliding with the ceramic target of Fig. 3. (b) The same event at the same moment in time as simulated with the HULL hydrocodes. (See "Modeling Armor Penetration" for a discussion of the hydrocodes.) The light blue areas in the computer simulation are regions of failed ceramic that do not appear in the radiograph because of lack of resolution and the tight confinement of the ceramic by the target holder.



rubble flows from the impact hole, it pushes inward and attacks the jet from the sides. In the case of long-rod penetrators, material flows out the hole but does not appear to attack the sides of the penetrator as it goes.

From these experiments, we should obtain radiographs of the dilatancy mechanism in action and accurate materials data on such things as the hardness of the ceramic, One of the main points of the tests is to accumulate more accurate experimental data to validate code-modeling parameters for armor and anti-armor designers.

Although the PHERMEX experiments provide valuable data, several fundamental questions about the dynamic behavior of ceramic armor are more easily addressed in laboratory experiments. One question concerns the *sequence* of events-does fracture occur at the rear of the ceramic (Fig. 4) during the passage of the initial shock wave or later as the penetrator forces its way through the material? In addition, scientists must determine what factors dictate the size and shape of the individual fractured particles and then understand how to model penetration of the resulting pulverized material.

To address such questions, Los Alamos scientists have designed two experiments that complement the PHERMEX ones. The first is a shock-recovery experiment in which a flyer plate propelled by a gas gun impacts a ceramic sample. Elaborate techniques are used to ensure that the specimen is subjected to a *single* shock loading and release of uniaxial strain. Scanning and transmission electron microscopy of the recovered specimen provide insight into the failure mechanisms during shock deformation. A second flyer-plate experiment uses a specimen assembly designed so that tensile waves from the rear of the specimen meet those from the front of the impactor (tensile waves stretch the material and are generated, in this case, as a release of the initial compressive wave). The superposition of these waves creates a large tensile pulse and rapid tensile failure, called spall, of the specimen. Determining spall strength in this way gives a qualitative, in situ measure of the fracture strength of the ceramic *after* the initial compressive shock has passed and caused any potential alterations of material properties. In addition, post mortem characterization of the fracture surfaces provides data on fracture mechanisms.

Although the veil of smoke and confusion has not been totally cleared, PHERMEX is letting us view and identify the major events that occur when a penetrator impacts ceramic armor. ■

Modeling Armor Penetration

by Ed Cort

Armor and anti-armor technology is becoming increasingly complex, forcing weapons designers to rely more and more on computer modeling. For years, computer simulations of armor penetration contributed only modestly to armor development compared, say, to the role of computational fluid dynamics in the aircraft and aerospace industries. However, computer modeling is becoming a major tool in the study of armor-penetrator interactions by offering weapons designers a number of distinct advantages in their quest of an essential understanding of the processes.

For example, the destruction and the speed of ballistic penetration make experimental diagnostics expensive, difficult to interpret, and, in many cases, impossible to gather. In comparison, a computer simulation, when benchmarked against even limited test data, can "replay" the experiment in slow motion. Computer modeling can also resolve velocity and stress and strain components in the target and penetrator in fine detail and pinpoint the relative interaction between armor components. The role of penetrator velocity, plate spacing in multilayered armor, and yaw (the angle of the penetrator's axis with respect to its velocity vector) can be assessed easily, and armor designers can test their understanding and arrive at new insights by changing and optimizing such parameters. The results of a computation. done *before* the experiment can be used to guide test design by answering questions about the most advantageous locations for the instruments, the proper scale ranges for recording data, and the important experimental variables.

The goals of the computational research being carried out under ATAC's direction are to validate and benchmark codes and methods, to pinpoint areas of needed research, and to improve existing codes-especially the ability to deal with a three-dimensional modeling of impact and penetration.

The *hydrocodes* used in the simulations are grounded in classical continuum mechanics, which attempts to describe the dynamics with a set of differential equations bed on the conservation of mass, momentum, and energy. An equation of state relates the material's density, internal energy, and pressure. Finally, a constitutive equation describes the stress-strain relationship in the material and reflects changes in the properties of the material, such as work hardening that result from severe distortion. In fact, there is a frequent need to model the material *after* it has failed, a need that may sometimes distort the usual assumptions of continuum mechanics beyond simple extrapolation.

From a practical point of view, the ideal design code should have a user interface that allows problems to be set up conveniently, standardized material models and properties that can be expanded or modified easily, and powerful graphics and post-processing that can depict results quickly and in a manner that is easy to interpret. The code should be accurate in the physics and material behavior it intends to model as well as in the numerical implementation and programming that translate equations into code. The code must be adaptable to a wide variety of problems, efficient in memory use and running time (although, here, the definition of what is unacceptable constantly changes), and robust enough that the code does not fail when it encounters an unexpected situation.

The bulk of the computer codes used on a production basis fall into two categories: Eulerian and Lagrangian. Simply stated, Eulerian methods move the material through a fixed mesh as the problem progresses whereas Lagrangian methods have a computational grid attached to the material that distorts with movement of the material. (Eulerian codes are frequently used in fluid dynamics whereas Lagrangian methods are more often used in structural analysis,) Each method has its peculiar advantages and disadvantages. For instance, Lagrangian methods tend to be faster, can implement sophisticated material models more easily, are efficient with large problems, and treat material interfaces accurately. However, they also deal inaccurately with large shear flows, are more complex to set up, and are not robust with large distortions such as those that occur when armor penetration is significant. Eulerian methods are almost a mirror image of Lagrangian methods since they are robust, easy to set up, and capable of handling large shears and distortions. On the other hand, Eulerian codes tend to be less accurate in the treatment of material interfaces, inefficient in the use of computer memory, difficult to implement with more sophisticated material models, and generally slower in running.

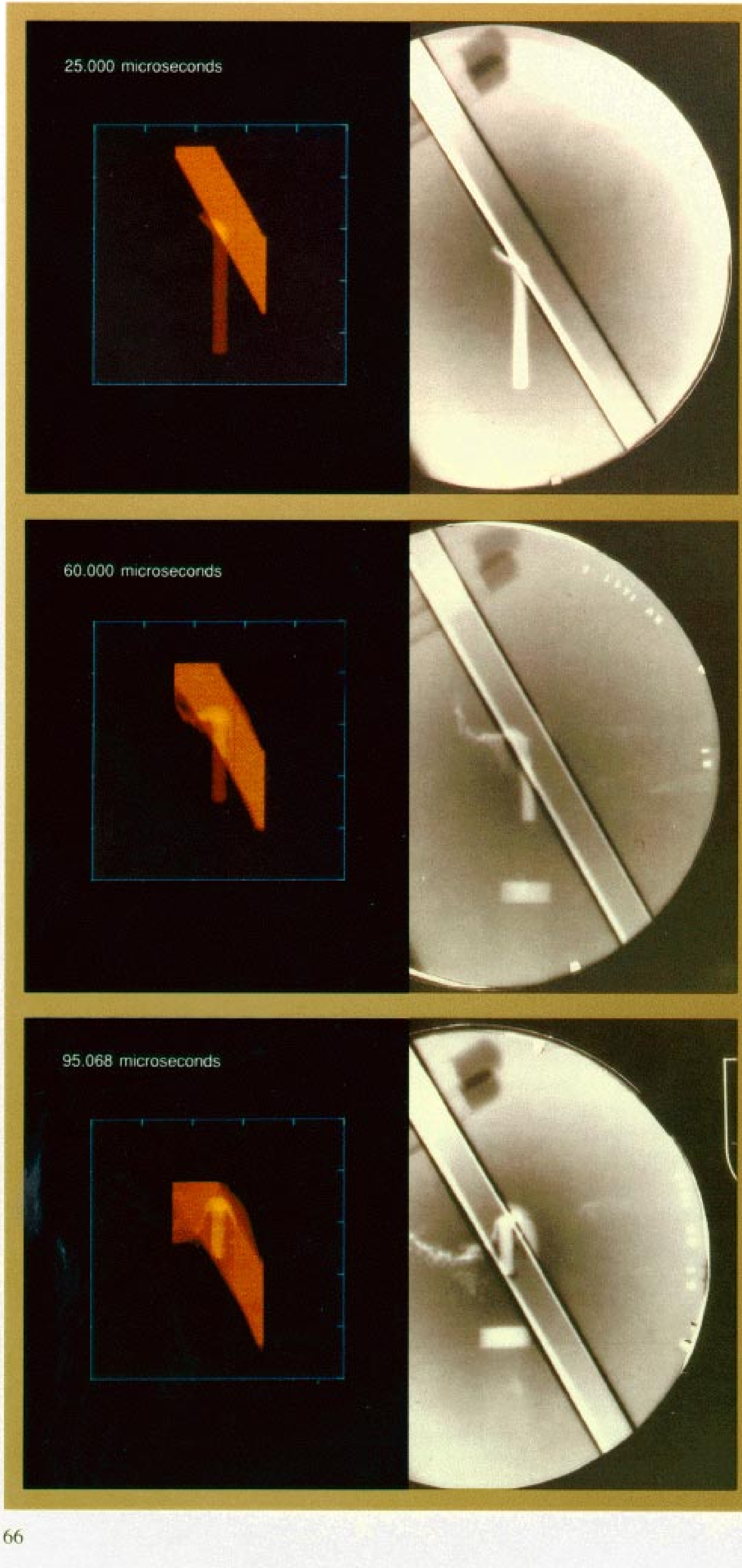
In our work at Los Alamos, we first explored an existing three-dimensional Eulerian code, HULL. We wanted to test its ability to accurately predict penetration of *spaced* armor, which has multiple layers of armor separated by gaps and set at oblique angles to the penetrator's line of flight. The intent of such a configuration is for the obliquity of the plates to deflect, bend, or break the long rod so that later plates can stop the residual pieces more easily. Reactive armor is another type of multilayered armor that also attempts to interfere with the rod's trajectory. In this case yaw is created on impact when a layer of explosive ignites, shoving a plate of armor toward the penetrator to knock it askew.

A computer simulation of the penetration of spaced armor plate will be realistic only if the code deals accurately with (1) the erosion of the front of the rod as it penetrates a plate, (2) the loss in velocity of the residual rod, (3) any changes in the orientation of the rod, and (4) the yielding and failure in the plate. We tested the ability of HULL to model armor penetration accurately by having it simulate a set of experiments carried out in the late 1970s using the PHERMEX machine. In these experiments, long-rod uranium-alloy Penetrators impacted steel-alloy plates set at various angles to the flight of the rod. Comparison of a PHERMEX radiograph and the corresponding computer simulation (Figure) illustrates how well the code predicted the interaction between penetrator and target.

These benchmark experiments gave us confidence that the code had the potential to provide useful information about similar experiments with more complex targets, such as ceramics, whose interaction with the penetrator was more difficult to model, But a computation of this type pushed HULL to the limit of its capability—it had a running time in a CRAY X-MP computer of 11 hours, and the computer memory would not hold enough information to model a second target plate with an intervening space. Even if larger computer memories were available, realistic targets-up to 10 times as thick as the preliminary example—would require considerably more computer time to model. Our evaluation was that HULL is a useful but limited code.

The evaluation, coupled with many other code comparisons, motivated us to develop a new three-dimensional code designed specifically for simulations of armor and anti-armor systems. The code, called MESA, is Eulerian and treats hydrodynamic flow and the dynamic deformation of solid materials. Because it uses state-of-the-art numerical methods, it runs faster and is less affected by spurious numerical problems than existing Eulerian codes. The version of MESA now being tested incorporates several of the standard strength models that take into account both the elastic and the plastic regions of the stress-strain relationship of the materials. There is also a programmed-bum model for the explosives. We have developed ‘a number of such models, which should increase our ability to simulate a variety of interactions for modern armor systems. In future versions of MESA we will include more advanced materials models.

One such model, called the Mechanical Threshold Stress model, will incorporate the physical deformation mechanisms needed to simulate conditions not easily achieved in the laboratory but important to this type of research. Specifically, the model will allow us to extrapolate better into regimes of high deformation rate, high temperature, and large amounts of strain. The model separates the kinetics of strain hardening (that is, dependencies on temperature and strain rate) from the kinetics related to the strength at a given instant. So far we have demonstrated the model only for certain well-characterized metallic systems, but we are extending it to the more complicated materials used in armor and anti-armor applications. We also hope to combine the defor-



BALLISTIC IMPACT—SIMULATED AND ACTUAL

The penetration of steel plate by a kinetic-energy rod as photographed with x rays generated by PHERMEX (right) and as simulated by the HULL hydrocode (left). Time increases from 25 microseconds after impact at the top to about 95 microseconds at the bottom, and the impact velocity of the rod is 1000 meters per second.

Table

Current application of MESA (funded by the Department of Defense and the Army Missile Command as well as DARPA, the Defense Advanced Research Project Agency).

- Nonaxisymmetric shaped-charge generators of explosively-formed jets.
- Penetration of reactive armor by jets.
- Effects on jet formation in TOW missile when:
    - two warheads are fired side-by-side, and
    - passive materials are placed nonaxisymmetrically adjacent to a single warhead.
- Penetration of armor by long rods with:
    - the rod trajectory impinging obliquely,
    - the target moving, and
    - various degrees of pitch and yaw.

mation kinetics of this model with the anisotropic deformation incorporated in some of the other models we are developing. Such a marriage has already been demonstrated in specialized problems, but we need to do further work to reduce the computational burden that accompanies the full analysis.

Another major application area for MESA is the reactive-armor problem. We foresee a need to model in some detail the interaction of projectiles with these sandwiched layers of metal plate and explosive. When the shock wave produced at impact detonates the explosive, the plates are set in motion and interact in a complicated fashion with the projectile. Not only is this problem three-dimensional, but interface resolution must be accurate because the moving plates are thin. A related problem is to predict the loads on the underlying vehicle structure due to the reaction forces of the flying plates and the blast. To demonstrate the usefulness of MESA for reactive-armor problems, including estimating the loads on the vehicle, we have simulated the dynamics of a two-dimensional analog of typical reactive armor. The results are very encouraging because they show that the contorted deformations can be resolved reasonably well with a computational grid that consists of only about four cells across the thickness of the plate.

Currently, we are testing MESA and applying it to a variety of armor/anti-armor problems (see Table). Following this initial phase, we hope to transfer the code to other interested members of the armor and anti-armor community that might need to use it. ■

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