Los Alamos Science

LOS ALAMOS NATIONAL LABORATORY

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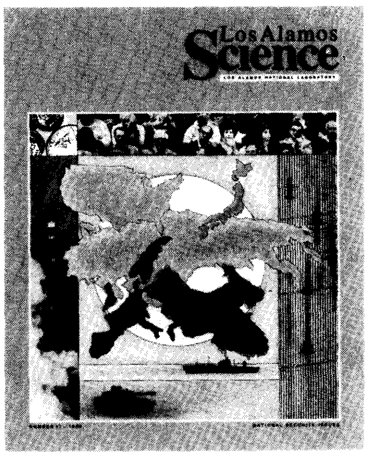
NATIONAL SECURITY ISSUES



In contrast to the postwar era in which the United States (blue) and Russia (yellow) were the two dominant powers, the rapid growth in technological, economic, and perhaps military power of Japan (green), China (red), Western Europe (brown), and other regions is making those nations into world powers as well. A conference sponsored by the Laboratory on "The Future of Nuclear Weapons—The Next Three Decades" explored this theme as well as the impact on nuclear weapons policy of public opinion (top), economic trends (upper left), military needs (left and bottom), and science and technology (right). The last theme is represented by a seismic recording of an actual underground nuclear test, a technology of key importance to verification. (Cover art by Gloria Sharp.)

Los Alamos is known worldwide as the birthplace of the atomic bomb. For the last forty-six years the Laboratory has remained the leader in development of nuclear weapon technology—leadership meant to guarantee a world safe from global conflict. The paradoxical role of nuclear weapons (peacekeeping through the threat of mutual assured destruction) is hard for any one to fathom without developing a simplistically polarized viewpoint. As the world grows more complex it appears to many that world stability must come to rest on other limits.

What will be the future of nuclear weapons? Will the public continue to support their role as a peacekeeping force? Are there any immediate alternatives? If not, can the Laboratory maintain its preeminence alongside growing perceptions that nuclear weapons may become irrelevant or too difficult to maintain?

When Sig Hecker became Director of Los Alamos in 1986, he faced the challenge of guiding the Laboratory through an evolving political climate. To understand that climate and to forge an appropriate and necessary role for the Laboratory, Sig created the Center for National Security Studies. The Center is a mini think tank that will help to shape technological decisions through careful consideration of changing political realities. One of the early projects of the Center was sponsorship of an unprecedented conference whose title, "The Future of Nuclear Weapons—The Next Three Decades," states the major concern of this institution. In the article "Debating the Future," members of the Center report on the conference with a spirit of objectivity reflecting the seriousness of the issues. They do not attempt to predict the future. Rather they set before us the many ambiguities, diverse opinions, and conflicting changes that make decision-making difficult. In response to the conference report, Sig Hecker offers his view of the role of the Laboratory-a view that will undoubtedly evolve along with the rapid changes we must all somehow adapt to. Sig emphasizes the need to maintain nuclear competence and explains in simple terms what such competence entails. We cannot take for granted the delicate fabric of working scientists and stored experience that this Laboratory represents. It has undoubtedly been a mainstay of our sense of security, and the continued health and vitality of its programs are crucial to the future of our nation.

Solving urgent national problems is the living heritage of those who work at the cutting edge of nuclear weapons technology. Among those problems is a particularly difficult one: How do we redesign nuclear weapons with the necessary confidence in performance in a time of reduced, restructured, or prohibited nuclear testing? We hope such questions will stimulate our readers to rethink the complex issues and choices presently before us.

One of the major changes occurring right now is a decreased reliance on nuclear weapons as tactical alternatives and a greater reliance on conventional weapons. The Laboratory has been involved in conventional weapons for many years, but that role is now increasing. In this issue we report on one of the areas in which the Laboratory is making a significant contribution—the area of conventional tank warfare. It is well known that the Soviet Union relies heavily on the strength of its armored forces and invests heavily in modernizing those forces at regular intervals. In contrast, the United States lags behind in deploying the technology developed at research laboratories such as Los Alamos. Don Sandstrom, the inventor of a new type of ceramic armor, reports here on the major advances in the development of materials for armored vehicles and for the projectiles that penetrate armor. In "Armor/Anti-Armor—Materials by Design," Don explains the technology, computer simulations, and diagnostic techniques used to develop the new materials. In a follow-up article Phyllis Marten and Richard Mah describe a unique collaboration between industry and the Laboratory that will facilitate the movement of those technological advances from the laboratory bench into the field. This effort is just one among a number of programs in conventional and non-nuclear weapons development in which the finely tuned expertise developed in the nuclear weapons program is being used to great advantage.

Since the topic of this issue is national security, we should point out that the concept of national security encompasses more than just weapons but rather the health of the nation. As such the Laboratory sees its role as being much broader than weapons development and includes in that role the application of science and technology to many national problems and challenges. In that vein, Laboratory scientists are tackling such topics as high-temperature superconductivity, supercomputing, the human genome, and even the AIDS epidemic, the topic of our next issue. ■

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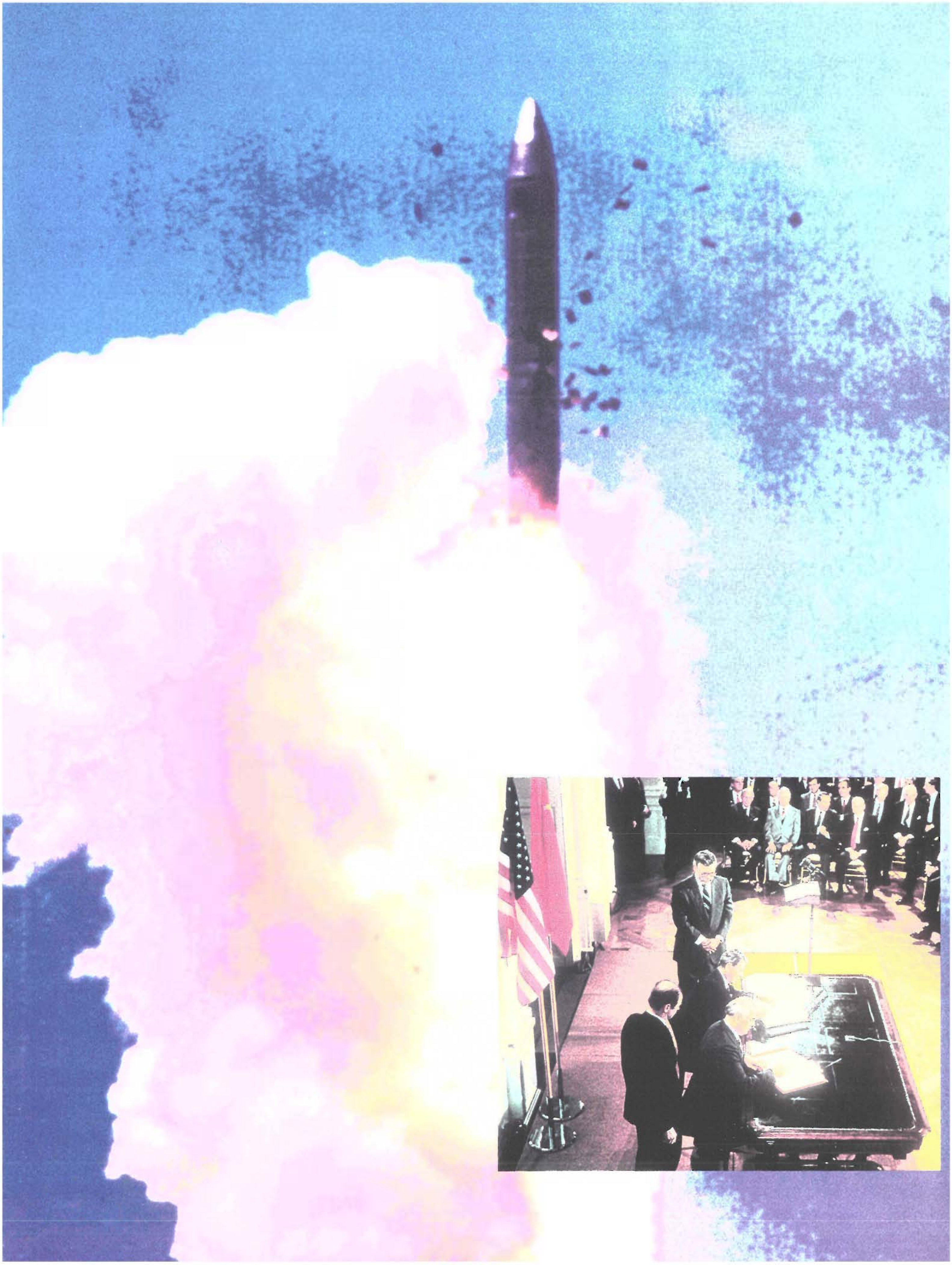
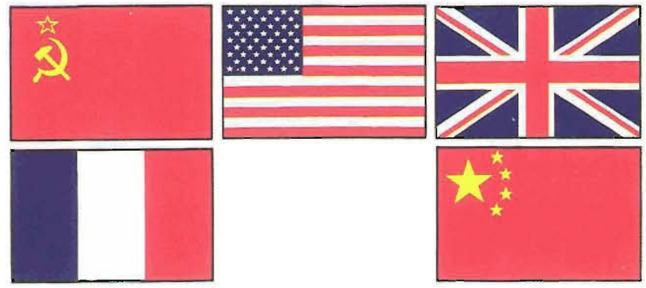




THE FUTURE OF NUCLEAR WEAPONS

The Next Three Decades

THE FUTURE OF NUCLEAR WEAPONS

An Introduction

by Paul C. White

Some forty-six years ago many of the best scientists in the world assembled on a mesa top on the eastern slopes of the Jemez Mountains of northern New Mexico. They arrived in a steady stream, carrying secret military orders, often traveling under code names to conceal their identities. Many of them did not know the real nature of the project they came to work on until after they had arrived. But, coming as they did from a United States and a Europe gripped in the throes of the Second World War, all of them firmly believed that they were there to undertake a scientific challenge characterized by great technical difficulty and tremendous political urgency. They had been assembled to develop a nuclear explosive, an "atomic bomb," and they absolutely had to be the first in the world to do it. If they failed and Germany developed a nuclear weapon first, then Hitler would win the war. If the New Mexico scientists won the race, then the United States and the Allies would save the world from Nazi domination.

The scientists faced an enormous set of technical challenges. To begin with, neither the physical nor the nuclear properties of the fissionable isotopes of uranium and plutonium were known. These materials wouldn't even exist, in other than laboratory samples, until they could be produced in the nuclear reactors and the isotope separation plants of the Manhattan Project. The necessary data had to be verified by experiments often conducted on minute quantities of the rare materials. Neutron transport models had to be devised, fission cross-sections had to be measured, and new diagnostic techniques and instrumentation had to be developed. To produce a nuclear explosion, the fissionable materials had to be acted upon by chemical explosives. In the case of the implosion device, the timing of explosive detonations and the focusing of the detonation waves were new hurdles that had to be overcome. These and other challenges were met by teams of dedicated scientists, working often under makeshift conditions and certainly under extreme time pressures.

One of the most significant aspects of this massive undertaking was that a successful outcome was by no means certain. No one knew for sure that a nuclear explosion could be generated, and success would come only if a whole series of technical problems could be solved. Even if solutions were found, it was not clear until late in the war whether the Germans might find them first. This uncertainty created both

Center for National Security Studies

The Center for National Security Studies exists at Los Alamos to provide the Director and the Senior Management with insight into the connections between national security policy and technology issues. In recent years the relationships between the Laboratory and its programmatic sponsors have become more and more complex. Paperwork and layers of bureaucracy interfere with clear communication and direction about national priorities. Budget actions often seem remote from the technical requirements of the Laboratory's traditional missions. The missions themselves are even being scrutinized and, in some cases, are being broadened to include technological applications in whole new arenas. In this changing world the Center tries to provide a broad perspective on policy issues related to national defense. It is hoped that this perspective will better equip the Laboratory to make decisions about technical priorities and directions.

The Center approaches this objective in a number of ways. The staff is a mixture of professionally trained policy analysts and scientists drawn on rotating assignments from the Laboratory's technical divisions. Consultants and contract personnel experienced in the assessment of national policy issues multiply the effect of the Laboratory staff. The Center uses its collective resources to study and analyze themes similar to that of the Future of Nuclear Weapons project described in the accompanying article. This research does not attempt to make technical assessments; such assessments are the responsibility of the technical programs. Rather the Center seeks to take a broad, long-range view of the ways in which policy trends at the national and international level may affect program choices. The Center uses briefings and reports to communicate the results of its studies to Laboratory personnel, and it circulates the results among the wider policy analysis community in government, military, and academic circles, as well as private industry. The Center also sponsors seminars, workshops and conferences designed to bring Laboratory personnel into contact with outside experts and to improve the Laboratory's understanding of defense policy issues. Finally, the Center acts to enhance communication between Los Alamos and other organizations, such as colleges and universities, that are studying issues of interest to the Laboratory.

In an increasingly complex world, the Center is seeking to provide the broad background that will enable the Laboratory to make the best possible technical decisions. The Center stands as a link between the internal technical community of Los Alamos National Laboratory and the external policy community that can have such a profound effect on the Laboratory's mission and programs. ■

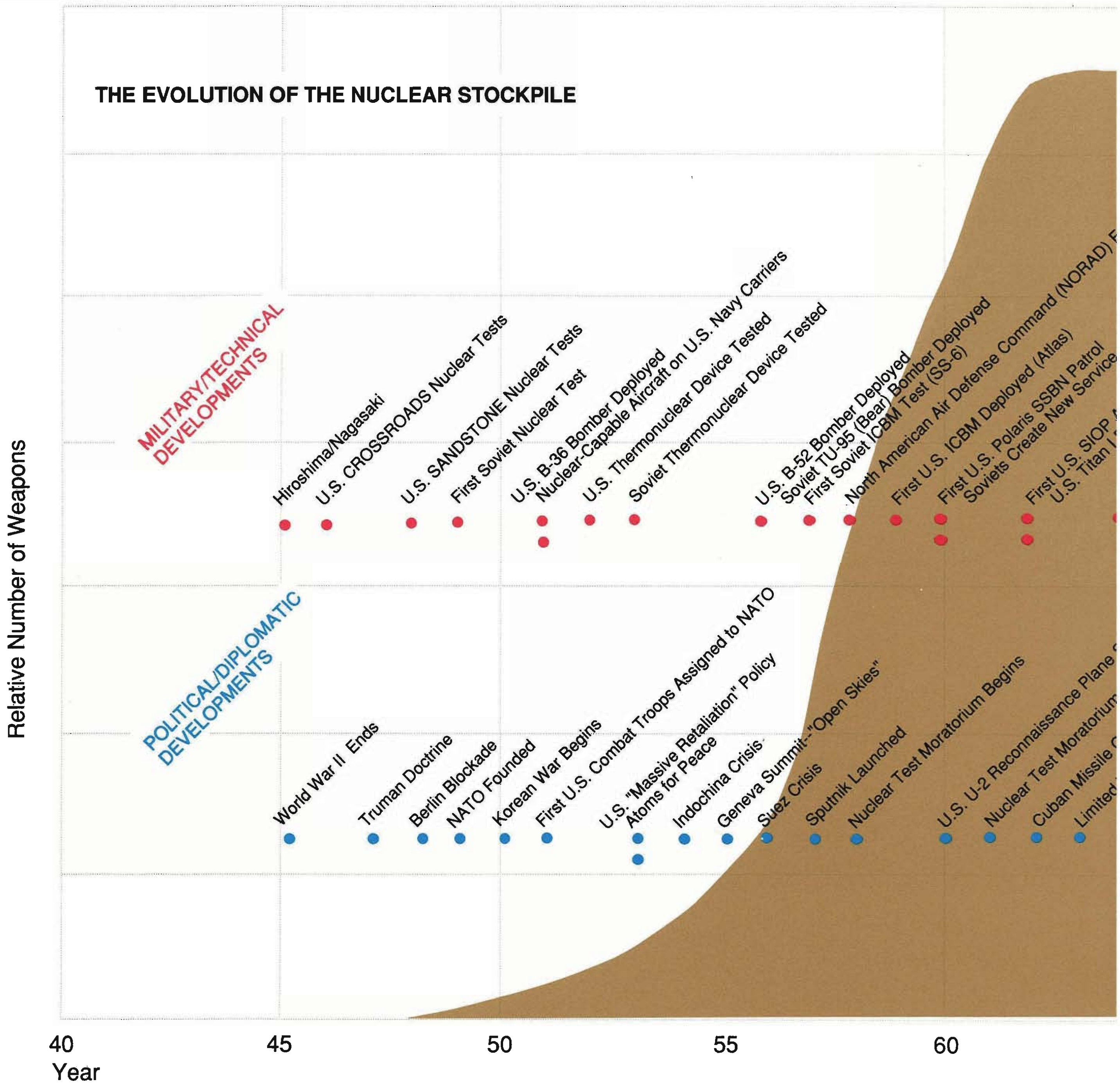
For further information, call or write to: Center for National Security Studies, Los Alamos National Laboratory, P.O. Box 1663, MS A112, Los Alamos, NM 87545.

a universally shared sense of political urgency and a heightened feeling of technical challenge. The first Los Alamos scientists were charting new scientific territory, and a special combination of scientific and political motivations drove them to be first.

Their spectacular success was brilliantly apparent one July morning in the New Mexico desert. Later that summer, the first nuclear weapons were used to devastating effect at Hiroshima and Nagasaki, the first and last time nuclear weapons were ever used in war. Many have argued whether this use was ultimately necessary to end the war, but no one could doubt either the magnitude of the technical accomplishment or its significance for the future of conflict between nations.

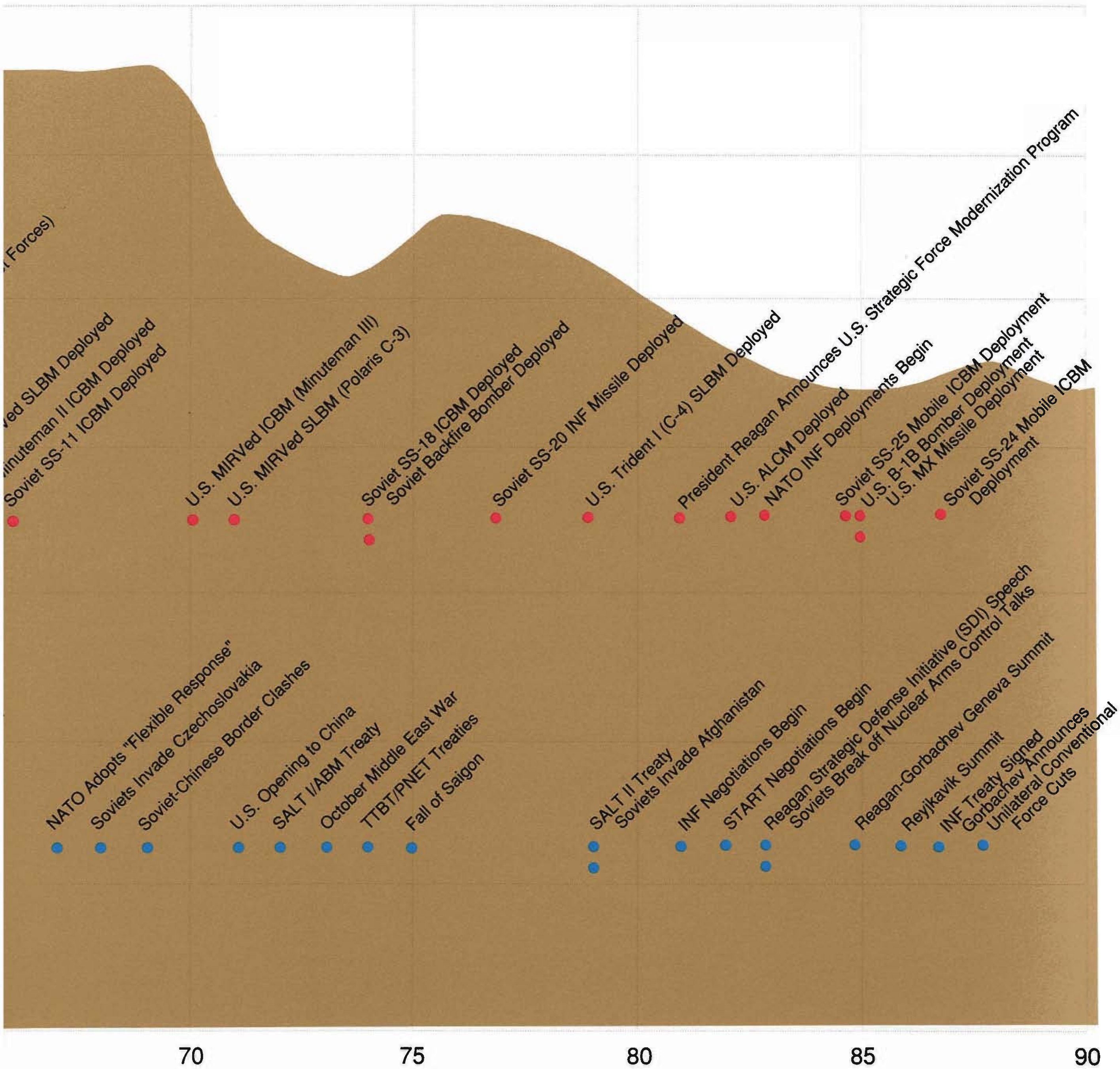
The Present

Los Alamos National Laboratory, along with its sister laboratories of Livermore and Sandia, today stands as a symbol of the continuing role played by nuclear weapons in international relations. Time and again in the years since World War II, the nation has called on its nuclear weapons laboratories to produce new technologies in support of the national security policy of deterrence. Today great nations do not use nuclear weapons to end wars but to prevent them. For example, the United States can threaten the possible use of our nuclear weapons against any adversary contemplating aggression. The threat is intended to be sufficiently credible and to suggest such unacceptable consequences that no potential adversary



would risk a significant attack against the United States or one of its allies. For nearly forty-five years this policy has been highly successful, at least to the extent that no nuclear weapons have been used since their first use, and no major conflict has erupted between the major powers.

To support the policy of nuclear deterrence, the national weapons laboratories have worked with the Departments of Defense and Energy to design and develop nuclear weapons with a wide ranging set of characteristics. The stockpile of today (Figure) consists of a large variety of weapons with different designs, sizes, weights, delivery modes, and yields. Such variety is intended, in part, to ensure that the deterrent forces are survivable, deliverable, and effective. Using delivery vehicles that range from submarine-launched ballistic missiles to air-launched cruise missiles, helps ensure that enough forces will survive to make a retaliatory strike credible, regardless of the circumstances of an attack. The spectrum of weapons yield and nuclear effects helps ensure that a nuclear strike can inflict damage that is unacceptable to a potential adversary. Over the last four decades specific requirements to meet these objectives have changed, both as national policy



has evolved and as the characteristics of potential targets have shifted.

Providing the technical resources necessary to respond to such changing requirements is one of the principal reasons for the existence of the national nuclear weapons laboratories. The laboratories support national policy, however it adapts to changing circumstances, by serving as unique sources of scientific capability. In particular, the weapons laboratories offer a broad technology base out of which new requirements can be met. Such requirements continue to include applications directly related to weapons design and effects, such as the ability to defeat newly hardened targets. There is also a continuing and, indeed, growing demand for the application of defense science insight to improved verification of arms control agreements. To respond to all such issues in a timely fashion, the laboratories are finding they must determine technical program priorities well in advance of the stated requirements, and in the context of a complex and changing national and international security environment.

The Future

The Center for National Security Studies was established in 1986 to help the Laboratory properly interpret the national security policy environment within which it must make technical program decisions (see "The Center for National Security Studies"). The Center undertakes research and analysis projects that explore the long-term relationships between broad national security issues and the Laboratory's most important technical programs. The nuclear weapons program is clearly one of these, and a project known as The Future of Nuclear Weapons was one of the first studies undertaken by the Center. As noted above, many consider that the special combination of deterrence policy and nuclear weapons systems has for several decades provided a stable relationship among the major nuclear powers. However, the world has not remained static, and a number of factors have combined to raise important questions about the future of nuclear weapons and the role they will play in the world.

In the Soviet Union, for example, pressures for economic restructuring appear, at least for the near term, to be reducing the emphasis on strategic competition with the West. The resulting general appearance of reduced tensions, combined with such specific consequences as the Intermediate-range Nuclear Forces (INF) Treaty, are leading to a new debate in Western Europe about future requirements for Alliance security. Some of this discussion also derives from the increasing political and economic multipolarity of the world. Emerging economic powers in East Asia and the growing military potential of other nations are straining old alliance relationships and broadening the focus of concern about international security. Finally, public opinion, particularly in Europe and the United States, is forcing a new look at the roles of nuclear weapons and the resources required to support them.

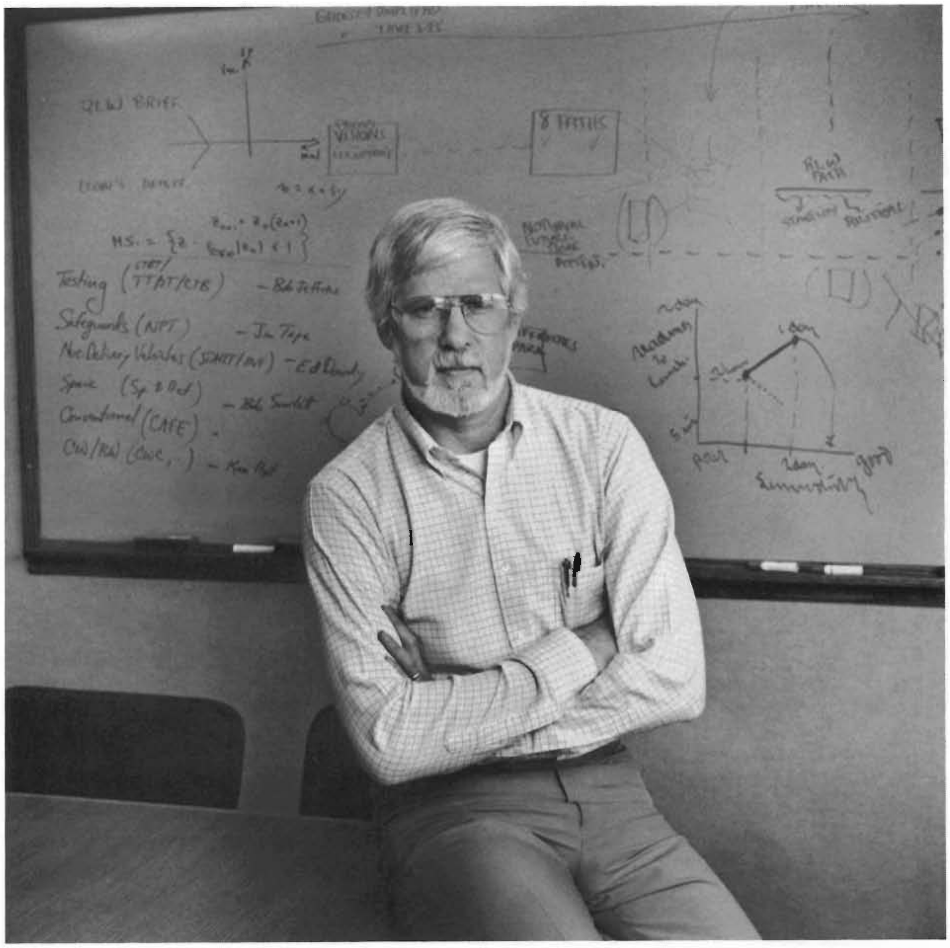
If there are major changes in the way the world and the country think about nuclear weapons, such changes would have a profound effect on the Los Alamos National Laboratory. The Laboratory has a long and distinguished history of providing the technical basis for the design, manufacture and maintenance of nuclear weapons that support the country's national security policy. About two-thirds of the nuclear weapon types in the U.S. stockpile were designed at Los Alamos, and much of the innovation that provides for improved stockpile safety and meets new stockpile requirements continues to originate here. The Laboratory has also been a source of new ideas that have enriched the scope of thinking about future nuclear weapons policy. Nuclear weapons and related programs comprise a significant fraction of the total Los Alamos budget and involve about half of the total Laboratory work force.

The possibility that national thinking about the role of nuclear weapons may change must, therefore, be an important part of the Laboratory's planning. In fact, this possibility prompted the Center for National Security Studies to undertake the Future of Nuclear Weapons project. It is hoped that the project will provide the Laboratory with the crucial background information needed to make decisions about the future character of the nuclear weapons program at Los Alamos. The questions that must be asked include:

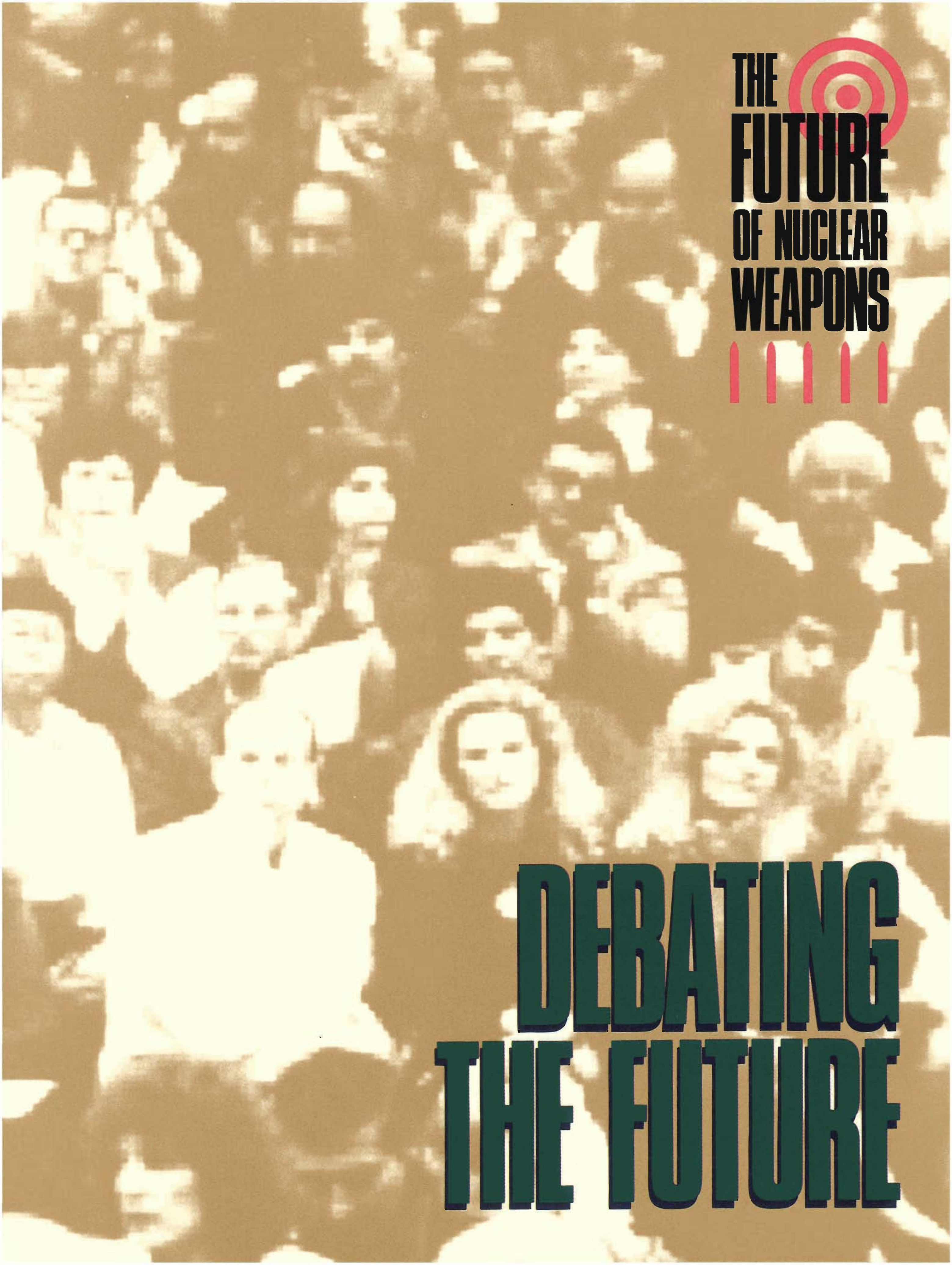
- How will the deterrence policy of the U.S. evolve over the next several decades?
- How will any shifts in that policy affect the requirements of our nuclear force structure?
- What technical demands will be placed on the nuclear weapons laboratories to support those future requirements?
- How can the laboratories best proceed now to ensure that they retain the technical capability necessary to support future U.S. nuclear policy?

A recent conference sponsored by the Center addressed some important aspects of these questions. A number of national experts were asked to assess major factors that help shape U.S. nuclear policy. They presented their preliminary analysis to a distinguished audience gathered from government, academic and military circles, and the nuclear weapons laboratories. Extensive discussion then helped to refine the thinking, and some preliminary conclusions are examined in the following article. In a third article, Dr. Siegfried Hecker, the Director of Los Alamos National Laboratory, responds to issues raised by the conference about the future role of Los Alamos. He also discusses changes that may be necessary to position the laboratory to support the national security requirements of the future. Ultimately, the Center will publish the results of the Future of Nuclear Weapons analysis as a volume in its book series *Issues in National Security*.

The early Los Alamos scientists, working under wartime pressures, clearly recognized the significance of their technical work to the nation's security. The leaders of the project, including its director, Robert Oppenheimer, met directly with the highest government officials to determine priorities and the allocation of resources. Interactions with government and with the national security environment have become more complex in the decades since. However, the importance of the Los Alamos nuclear weapons program to national security policy has in no way diminished. The Center for National Security Studies hopes that programs such as the Future of Nuclear Weapons study will help the leaders of Los Alamos to continue providing the best possible technical resources in support of the national interest. ■



Paul C. White is currently the Acting Director of the Center for National Security Studies at Los Alamos. He earned his Ph.D. in physics in 1970 from the University of Texas at Austin, where he pursued research on general relativistic transport theory and cosmology. Prior to coming to Los Alamos, he taught physics and astronomy for six years at St. Edward's University in Austin. Since joining the Laboratory he has, among other things, been the Laboratory Program Manger for Advanced Nuclear Weapons Design Technology and served as a member of the U.S. delegation to the Nuclear Testing Talks in Geneva. He joined the Center as its Deputy Director in the summer of 1986.



THE FUTURE OF NUCLEAR WEAPONS

DEBATING THE FUTURE

The past decade has seen a number of significant challenges to the role of nuclear weapons and to the security policy of nuclear deterrence that these weapons support.

Five years ago President Reagan announced his goal of making nuclear weapons "impotent and obsolete" by creating defenses against the threat posed by intercontinental ballistic missiles (ICBMs) armed with nuclear warheads. This goal has engendered within the United States an intense and continuing battle over the proper role of offensive strategic nuclear systems in a policy of deterrence.

Thus, a spirited debate has risen in the Congress, the press, and the public over recent proposals for *strategic modernization*, in which older nuclear weapons that are frequently obsolete and not fully capable of meeting new mission assignments are to be replaced with newer weapons. Such proposals raise a number of vexing questions. Are deterrence and strategic stability best served by moving to a single-warhead "Midgetman" missile, or should the United States invest in a new, land-based ICBM with the multiple warheads of a MIRV system? Should we continue to rely on fixed-silo ICBMs, or should we adopt a new generation of mobile missiles? Are cruise missiles a stabilizing or a destabilizing development? How should cruise missiles be armed? What should be done with the potential of stealth bombers?

Similar questions are being asked in Western Europe, the principal overseas location of U.S. nuclear weapons. In 1979 NATO made a "dual-track" decision to replace aging U.S. nuclear systems in Europe with newer, more effective weapons—Pershing IIs and ground-launched cruise missiles—while simultaneously pursuing negotiations with the Soviet Union to reduce or eliminate the need for such systems. However, deployment of these systems became the focus of massive street demonstrations and parliamentary debates. Such conflict challenged the basic NATO policy of relying on nuclear weapons to keep at bay aggression from the Warsaw Treaty Organization. Although the NATO modernization program was begun, it has since been reversed, as President Reagan and Soviet President Mikhail Gorbachev, in May 1988, exchanged instruments of ratification for the Intermediate-range Nuclear Forces (INF) Treaty. The treaty eliminates all Soviet and American ground-launched missiles with ranges between 500 and 5,500 kilometers and has been widely hailed as a major breakthrough in the superpower arms control process.

The central theme that emerged from the conference was that we should expect changes, perhaps significant ones, to occur in the roles played by U.S. nuclear weapons over the next three decades.

And we now seem to be entering an era with the potential for real reductions and restrictions of nuclear arms. The INF treaty may be followed by an even more significant agreement to reduce substantially long-range offensive weapons. The current negotiations in this later area are known as the Strategic Arms Reduction Talks (START). At the same time, the United States and the Soviet Union have been engaged in extensive talks about how to verify limits set on nuclear testing. The Nuclear Testing Talks resulted in two Joint Verification Experiments in August and September of 1988 that allowed weapons scientists of both sides to visit the nuclear test sites of the other and to develop methods for verifying compliance with test restraints. In addition, talks continue in Geneva on "Defense and Space" arms control—talks that consider the issue of defenses against ballistic missile attack, including defensive systems based in space.

A different kind of challenge to nuclear weapons policies arose in 1988 when safety and environmental problems began to emerge from the complex of facilities that produce weapons materials. Some people have used these incidents to question whether the U.S. can continue to support even current levels of activity in the nuclear weapons program.

We are clearly at a crucial point in the history of nuclear weapons technology.

A Public Forum at Los Alamos

The turmoil over these issues reflects a worldwide reconsideration of international security, including the role of nuclear weapons in deterring war. Thus, the time is ripe for a thorough review of the role of nuclear weapons in the defense of the United States and our Allies.

To consider the full range of political, military, and technological influences on U.S. national security policy—and to explore possible "nuclear futures"—the Los Alamos Center for National Security Studies (CNSS) sponsored a major conference in June 1988. One hundred and fifty persons from government, the military services, academia, industry, and the Department of Energy laboratories met in Los Alamos to review the past and to consider the future of nuclear weapons. The participants were chosen to provide the best expertise and a wide range of political views, including those of former government officials from Democratic and Republican administrations.

This essay attempts to capture the essence of the discussion at the conference. We do not intend here to predict the future definitively or to ascribe a particular viewpoint to any, or all, of the conference participants. Rather, the purpose is to begin to think through our basic assumptions about nuclear weapons and their likely roles in the next century.

The central theme that emerged from the conference was that we should expect changes, perhaps significant ones, to occur in the roles played by U.S. nuclear weapons over the next three decades. To be sure, the conference participants acknowledged that nuclear weapons are almost certainly here to stay, in some form and in some numbers, for the indefinite future. As in the past, the United States will continue to use its nuclear capability to deter major hostile actions by the Soviet Union and possibly by other states that may themselves possess nuclear (or chemical or biological) arms. This deterrent role appears to be the essential and irreducible role of nuclear weapons in American national security policy.

At the same time the conference discussion pointed toward future arms control agreements and unilateral U.S. decisions that will most likely lead to significant reductions in the nuclear stockpile over the next few decades. In addition to numerical reductions, the United States may gradually place less political and military reliance on its long-range, or strategic, nuclear forces (Fig. 1). Finally, the United States might decide to reduce greatly or even phase out certain types of nuclear weapons. This possibility applies most notably to the so-called *tactical* nuclear weapons, such as antisubmarine weapons and nuclear artillery shells—weapons that have been designed for local use on the military battlefield.

US AND SOVIET STRATEGIC NUCLEAR FORCES

Approximate numbers of delivery systems.	ICBM's	Submarine Launched Missiles (SLBM's)	Strategic Bombers
United States	1000	640	362
Soviet Union	1390	942	175

Fig. 1. A comparison of U.S. and Soviet strategic nuclear forces in 1987, which includes intercontinental ballistic missiles (ICBMs), submarine-lauched ballistic missiles (SLBMs), and heavy bombers. The numbers were taken from "The Military Balance, 1988–1989" (published by the International Institute for Strategic Studies, London: 1988) and "Soviet Military Power: An Assessment of the Threat 1988" (published by the U. S. Department of Defense, 1988).

To understand the meaning and implications of these themes, we will first review the current U.S. view of nuclear deterrence and the political and military utility of nuclear weapons. This background will then help us explore the critical questions examined at the conference: What roles might nuclear weapons play in future U.S. national security policy? Will these roles resemble those of the past decades, or are we moving into a different era? And what are the potential changes in the political, technical, and military environments that might bring about significant shifts in U.S. nuclear-weapon systems and deployments?

U.S. Nuclear Weapons: Today's Roles and Requirements

Discussions of the role of U.S. nuclear forces in American foreign policy and military strategy invariably invoke a single word: deterrence. The United States seeks to deter war by persuading a potential aggressor that the costs and risks of hostile action exceed any possible benefit. Because nuclear weapons are so incredibly destructive and relatively inexpensive—compared with other instruments of warfare—the United States has come to rely heavily on nuclear systems to drive home the idea that war is futile.

To back up this relatively simple con-

Because nuclear weapons are so incredibly destructive and relatively inexpensive—compared with other instruments of warfare—the United States has come to rely heavily on nuclear systems to drive home the idea that war is futile.

cept of deterrence, the United States has deployed thousands of nuclear weapons on a variety of missiles, aircraft, and other delivery systems. Some weapons are based in the United States, others on ships and submarines at sea, and still others on the territory of allies. These weapons vary considerably in yield (explosive power), range, and age (the oldest weapons now in stockpile were designed and built approximately thirty years ago). Some nuclear weapons are designed for long-range use against important political and military targets in the Soviet Union; others are intended for shorter-range employment against hostile forces in or near the actual battlefield. The U.S. military has devised elaborate plans for peacetime storage and training, crisis deployment, and wartime use of these nuclear systems.

Why has such a simple goal, deterrence, led to such a large and complex nuclear organization? The answer is that, under the general framework of deterrence, the United States makes considerable and specific political-military demands on its nuclear forces. For instance:

- Nuclear weapons must deter the Soviet Union, or any other hostile power, from attacking military targets and population centers in the United States. To ensure such deterrence the United States must be equally capable of destroying, or "holding at risk," critical military targets and urban-industrial centers in the Soviet Union.

- Nuclear weapons, in conjunction with forward-deployed land, sea, and airforces, must help deter the Soviet Union from attacking vital overseas allies and interests. The United States has explicitly or implicitly linked its "nuclear umbrella" to Western Europe, Japan, and U.S. interests in the Middle East. To ensure such *extended deterrence*, U.S. tactical and strategic nuclear forces must hold at risk the critical military targets, both fixed and mobile, that might support a Soviet campaign in the theater.

- Nuclear weapons must also reassure U.S. allies of American seriousness and responsibility with respect to allied defense. From the allies' perspective, the U.S. nuclear guarantee should be good enough to deter the Soviets but not so good as to frighten their publics or raise the prospect of "limited" nuclear wars fought on their soil.

- Nuclear weapons must not themselves be the cause of war. That is, the number, type, and peacetime operation of U.S. nuclear forces should not encourage or panic the Soviets into attacking because they must "use or lose" their own nuclear weapons in a crisis. This requirement for American nuclear forces is generally referred to as *crisis stability*.

- Nuclear weapons must be able to perform specific military operations if deterrence should fail—especially those missions that are not well suited to other types of weapons. For instance, enemy installations that have been strongly reinforced, or hardened, can only be destroyed with a nuclear explosion that is close to the target. Policy makers and military planners believe that such operational capabilities make deterrence more credible and hence less likely to fail.

Given these extensive and sometimes contradictory demands, American policymakers have sought to develop nuclear forces that satisfy a number of criteria. The criteria are survivability, flexibility, military effectiveness, affordability, discrimination, and safety and security (see box).

These attributes of U.S. nuclear forces have become very controversial over the past decade. The controversy is especially true for the characteristics that suggest the purpose of American nuclear weapons is to fight rather than deter war, that is, flexibility, military effectiveness, and discrimination. U.S. political and military officials insist, however, that deterrence and warfighting capability are complementary, not contradictory. Deterrence is said to be strengthened by capable nuclear forces that can meet aggression flexibly and effectively—without threatening to destroy enemy cities unless, of course, American cities are themselves attacked.

Future American presidents will place relatively more emphasis on the stabilizing aspects of nuclear forces and relatively less emphasis on extended deterrence, that is, on using nuclear weapons to reassure and protect allies.

The apparent tension between the *evident capability for warfighting* and the *concept of deterrence* is, in fact, a necessary condition for maintaining a deterrent relationship. To be effective, deterrent forces must not only be capable, but simultaneously the opponent must think it credible that the forces could be used effectively in the event of war. Credibility is provided precisely by the characteristics mentioned above required of nuclear weapons *and* by the detailed preparations for their potential use. This paradox—that for a deterrent force to deter wars, it must appear ready to fight them—is inherent in the very concept and practice of deterrence and will not change as a result of arms control, unilateral force reductions, or policy shifts, short of abandoning the concept of deterrence altogether.

NUCLEAR FORCE CRITERIA

***Survivability*: Nuclear forces must be survivable so they cannot be easily or promptly destroyed by an enemy attack. For instance, missiles can be made more survivable by making them mobile or placing them aboard submarines. Survivable weapons do not invite or pressure an enemy into striking first, and they do not tempt us to use them first because of a fear of losing the weapons in a pre-emptive attack.**

***Flexibility*: Nuclear forces must be flexible so we can deter or respond to a wide variety of enemy actions, including aggression against U.S. allies. Flexibility can be enhanced, say, by designing weapons with a full range of yields and designing carriers capable of delivering those weapons to a variety of targets.**

***Military effectiveness*: Our nuclear forces must be militarily effective so they can be called upon to destroy critical enemy targets if necessary. Effectiveness includes successful delivery of the weapon to the target as well as crippling the target once the weapon arrives.**

***Affordability*: The forces must be affordable so that the United States can deter war without bankrupting the country.**

***Discrimination*: Nuclear forces must be discriminate to minimize unwanted damage to the civil population while effectively destroying military targets. This may require tailoring the yield or the weapons effects to the particular military mission of the weapon.**

***Safety and security*: Nuclear forces must be safe and secure so that we may deploy the forces without fear of damage from accidents or their use by terrorists or others for unwanted purposes.**

U.S. Nuclear Weapons: Tomorrow's Roles and Requirements

How will U.S. nuclear roles evolve over the next thirty years? The sense of the conference, although by no means unanimous, was that the United States will tend to reduce the number and scope of demands placed on nuclear weapons. It is most likely that future American presidents will place relatively more emphasis on the stabilizing aspects of nuclear forces and relatively less emphasis on extended deterrence, that is, on using nuclear weapons to reassure and protect allies.

What would this shift mean, in turn, for future U.S. nuclear requirements? The growing emphasis on stability will cause the United States to place *relatively more emphasis on the survivability, safety, and security of its nuclear weapons and less on their military effectiveness and flexibility.* In particular, less emphasis would be placed on those nuclear weapons that could target Soviet nuclear forces. (The United States, however, is unlikely to abandon *all* such military capability for a very long time, if ever.) It is not clear how much this prospective shift would affect the requirements for affordability and discrimination, although one might predict a decreased level of funding for nuclear weapons programs and somewhat less attention to discrimination.

If this apparent trend toward stability and away from military utility and flexibility does prove out, how will the United States reflect such changes in its deterrence policy? Two possible approaches were discussed at the conference: *mixed deterrence* and *countercombatant deterrence.*

A policy of mixed deterrence would deter aggression using a mixture of nuclear and conventional weapons. The United States would retain small numbers of survivable, sea-based nuclear weapons to deter attack against its homeland by threatening the urban-industrial base (cities) of the Soviet Union and other hostile nuclear powers. Advanced conventional systems would then take over military missions formerly assigned to nuclear weapons, especially those involved in the extended deterrent role. Conventional rather than nuclear weapons would hold at risk the critical enemy military assets needed to support a campaign, such as airfields, troop concentrations, bridges, and command and control centers.

A policy of countercombatant deterrence would, the same as for mixed deterrence, reduce the mission of the U.S. long-range nuclear forces to holding the enemy's urban-industrial base at risk. However, a limited number of discriminate tactical nuclear weapons would be deployed in or near the probable theaters of military operations (such as Europe) to hold at risk the military assets needed to support a conventional invasion. The purpose of these theater nuclear weapons would be to complicate the enemy's military planning in the theater and thus enhance extended deterrence. The weapons would *not* be designed to fight and win a local nuclear war.

It is significant that no one at the conference explored the conditions under which the role of nuclear weapons in U.S. national security policy might *increase*. Even though the declining defense budget was discussed, no one suggested a return to a deterrent policy based on massive nuclear retaliation, which the Eisenhower administration adopted in the 1950s in response to its perceived fiscal problems. There was also no explicit discussion of the resumption of old nuclear missions, such as a new generation of tactical atomic mines, nuclear ship-to-ship or air-defense weapons, or nuclear antitank weapons. Nor, with the exception of the possible role of nuclear weapons in a future strategic defense initiative (SDI) system, did anyone raise the prospect of new nuclear missions. Only one suggestion went against this overall trend. Several participants suggested that if hostile regional states acquire nuclear or chemical-biological weapons, the United States may need to revise its nuclear doctrine and forces specifically to deal with issues raised by such proliferation.

It is important to note that the trend to de-emphasize the effectiveness and the flexibility of nuclear weapons could shift rapidly. Many of these same sentiments about fundamental changes in U.S. deterrence policy were also widely expressed at the beginning of the Carter administration, only to be altered dramatically by events at the end of the seventies, such as the unexpected Soviet invasion of Afghanistan in 1979. Most U.S. nuclear requirements are determined by considering how much weaponry is enough to deter the Soviet Union. Thus, the future of U.S. nuclear weapons is inherently dependent on the future direction of the USSR—a direction that no one can confidently predict.

The apparent trend toward survivability and away from military effectiveness, coupled with the possibility of a sudden reversal in priorities, represents a considerable challenge to the U.S. nuclear weapons complex. Los Alamos and the other parts of that complex are necessarily committed to excellence in preserving and improving our technological base in nuclear weapons. However, if the role of nuclear weapons in U.S. national security policy is perceived as declining, public and political support of a vigorous nuclear-weapons research and development program could well decline, as public interest grows in "turning off the arms race."

The potential for politically imposed constraints on weapons research and development is particularly visible today in the international and domestic pressures for limitations on nuclear testing. Testing limits, it is argued, are a necessary complement to arms control because they would prevent the development of new nuclear-weapon technologies. From a different perspective, however, conference participants cited how the need for technical excellence, and therefore testing, will increase as the numbers of weapons are reduced and the need to avoid technical surprise increases.

However, a new and potentially show-stopping factor emerged during and after the conference—severe safety and environmental problems within the nuclear material production complex. A series of reports about radioactive leaks to the environment and production facilities that are possibly damaged, as well as claims of inadequate operating procedures and management practices, have led to a virtual shutdown of critical elements of the nation's production complex. Continued uncertainty about the reliability of the operation of this vital system is sure to conflict with the need for excellence within the nuclear weapons system. There is a clear priority for technical and political action at both the national and the laboratory levels.

Political Influences

The most important trends indicating a gradual shift in U.S. nuclear roles and requirements are largely political in character. One session at the conference, for which Joseph Nye's opening remarks set the tone, explored the political influences on the future of nuclear weapons.

For instance, the current U.S. approach to nuclear deterrence—with its stress on flexibility and military effectiveness—was formulated in the context of the particular international and domestic environment that existed after World War II. The international environment was then dominated by a Soviet-American bipolar conflict, an environment in which U.S. allies and neutral states were economically and militarily weaker. The domestic American environment was marked by a bipartisan political consensus that the Soviet Union was an aggressive, expansionist power that needed to be contained, but the United States could not afford to deter Soviet aggression with *non-nuclear* defenses.

Many experts contend that this post-1945 pattern has changed substantially over the past twenty years and that it may be altered, perhaps beyond recognition, over the coming three decades. For example, if the threat of aggression is reduced or becomes less Soviet-centered, or if the pattern of U.S. overseas allies is significantly altered, or if nuclear systems become comparatively more expensive, then U.S. nuclear doctrine and force structure may focus increasingly on stability as opposed to military utility. There is no certainty that any, much less all, of these dramatic changes will occur, but the United States certainly should not assume that it will be "business as usual" through the year 2020.

The conference identified and explored four significant political factors that will, in part, drive future U.S. nuclear requirements:

- an international environment that is increasingly multipolar in political, military, and economic terms,
- the limits that U.S. and international public opinion may place on nuclear policy,
- the importance of arms control in U.S. national security policy, and
- the long-term effects of General Secretary Gorbachev's domestic reform program of *perestroika* (political, economic, and social restructuring) on Soviet military doctrine and on U.S. perceptions of the Soviet military threat.

We should also recognize that, as the world changes over the next thirty years from the familiar post-World War II pattern, our views of the utility of nuclear weapons may change as well. I think that U.S.-Soviet relations will remain a problem over time — whenever you have great powers you are going to have to manage a balance of power—but it will not be the same problem that we see today. In addition, we are going to be faced with proliferation. The proliferation of nuclear warheads, missile capability, and biochemical capabilities to other countries (and possible terrorists) is going to create a series of defense and security problems that could make today's Soviet threat pale into insignificance. I think the greatest prospect of a nuclear weapon going off inside the United States comes from the proliferation chain rather than through the U.S.-Soviet relationship ... I see the United States in the year 2018 as still the dominant power in the world, a power not in decline, but I see us facing much greater problems of a much more diverse sort. In that world nuclear weapons will play a role, but lesser a role than they have played thus far.

—Joseph S. Nye, Jr., Director, Center for Science and International Affairs, Harvard University, and the former Deputy to the Under Secretary of State for Security Assistance, Science and Technology, opened the session on political influences.

An increasingly complex world. By the year 2020 various nations, including Japan, China, and several Western European nations will, in all likelihood, command relatively more economic and political power than they do today. Japan, whose economy is the second largest in the world, will continue to exercise its influence. China's economy will continue to expand and may indeed rival that of Japan thirty years from now. By 1992 the twelve countries of the European Economic Community are scheduled to form a barrier-free market. They will thus confront the United States with an internal market of great strength.

Conference participants emphasized that, in light of these economic changes, the U.S. military alliance structure—including the American nuclear guarantee, or extended deterrence—will likely be affected in significant respects over the next thirty years. If American nuclear forces cease to be the central political and military element in NATO strategy, the most dramatic change could be in the relationship between the U.S. and Western Europe. This shift might be brought about by unilateral American decision, the preference of more nationalistic European governments (of either the right or the left), the creation of a European defense organization with its own independent nuclear force, or,

Fig. 2. Nuclear powers (red) are countries that both possess nuclear weapons and the means to deliver them to distant targets. Other countries are known to have detonated a nuclear device but have no significant stockpile and no sophisticated delivery vehicles (blue) or are states that possess advanced nuclear technology (tan). Still other countries possess the technology to build a nuclear weapon but have apparently not done so yet.

in an extreme case, the West German acquisition of nuclear weapons.

In Eastern Asia the nations of Japan and China have the potential to become regional military powers with strategic ambitions that may not coincide with the interests of each other, the USSR, or the United States. The most extreme change in this region would be the Japanese acquisition of nuclear weapons.

United States policy toward this more differentiated world will be complicated immensely by the likelihood that at least some second-tier states—such as, Iran, Taiwan, Indonesia, India, and others—may attempt to acquire nuclear weapons (Fig. 2). (We already have evidence that "proliferation" is taking place in the form of ballistic missile technologies and in submarine capabilities.) The spread of major military systems among second-tier states will pose increasingly difficult problems for U.S. foreign and defense policies and for the continuation of extended deterrence as we have known it for the past several decades.

In short, the United States will find itself in an increasingly complex international environment where U.S.-Soviet competition will only be one of several fronts that will demand American attention.

Some conference participants did not believe that the *political* utility of U.S. nuclear weapons would necessarily decline despite the increasingly multipolar character of international politics. The thesis that U.S. nuclear forces *do* offer indirect support to U.S. regional actions—for instance, the current Persian Gulf operations—and will continue to offer such support in the future was actively debated. Another thesis suggested that U.S. nuclear forces will continue to mark the United States as the only true military, political, *and* economic superpower, thus distinguishing it from all other states even thirty years from now.

Public opinion. A major shift in U.S. nuclear policy would occur if, as some suggest, nuclear weapons become "delegitimized"—that is, if the public refuses to support any policy or military deployment that involves nuclear weapons.

Analysis of public opinion data indicates, however, that there continues to be support for the concept of nuclear deterrence in the United States and NATO countries. By the mid-fifties American public opinion had come to accept the notion of international stability through mutual deterrence, or the ability of both the United States and the USSR to inflict unacceptable destruction upon each other. This acceptance continues today. But it is also true that other aspects of deterrence—especially the so-called nuclear warfighting, which involves military effectiveness, flexibility, and discrimination—has never had clear public acceptance.

> **United States policy... will be complicated immensely by the likelihood that at least some second-tier states such as Iran, Taiwan, Indonesia, India, and others may attempt to acquire nuclear weapons.**

Looking ahead thirty years, analysis indicates that there is no compelling reason why, if governments make the proper case for deterrence, Western publics will not continue to support nuclear weapons. Conference participants disagreed, however, over what constitutes a proper public case for nuclear weapons. A critical question arises in this regard. What circumstances might lead to a significant and permanent shift in the public perception of nuclear weapons—to the point that Western publics might reject a policy of nuclear deterrence altogether? Some at the conference suggested that a serious accident involving a nuclear weapon might trigger such an adverse public reaction. This danger makes it all the more important for nuclear weapons designers and operators to take the safety and security issue seriously.

Arms control. Many of the participants agreed that a strategic arms control agreement that would cut the number of long-range nuclear systems will be reached within the next several years. Over the longer term the case was made at the conference—not without opposition—that the arms control process will most likely support, and possibly drive, the shift from warfighting capabilities toward an emphasis on nuclear stability.

If this view is correct, future arms control policy would be aimed at restructuring nuclear forces to emphasize their survivability, thereby reducing perceptions of their possible use as weapons. This shift would be partly by design (it has been an objective of U.S. arms control policy for decades), partly by the force of technological change (the growing capabilities of non-nuclear weapons and possibly defensive systems), and partly by changing global circumstances. If long-range nuclear weapons are to be further reduced over this period, negotiations will have to include all important nuclear powers—at least France, the United Kingdom, and the People's Republic of China, in addition to the United States and the Soviet Union.

There was strong agreement at the conference that arms control, like nuclear weapons, is here to stay. Differences did emerge, however, concerning the rate at which substantial nuclear reductions might take place (decades or much sooner?) and over factors that might cause the arms control process to take a significantly different path.

The Soviet military threat. The perception of any significant change in the Soviet military threat has historically had a great influence on U.S. nuclear doctrine and weapons development. There was a consensus among the speakers that, in the near to mid-term, Soviet President Gorbachev will try to gain a breathing space in the strategic competition with the West to free resources for his economic restructuring program. To the extent that he can maintain a focus on domestic policy, the Western perception of the Soviet military threat will undoubtedly decline—with a predictable decline in the U.S. defense budget and nuclear weapons programs.

But will the threat really decline? Will Soviet leaders actually move toward a military doctrine (as they have promised) based on "reasonable sufficiency" and defensive emphasis? Assessing these questions will be difficult, if for no other reason than because the Soviets, even if sincere, will retain for many years a very large and capable military structure.

Unfortunately, we have not yet developed a set of key indicators that will provide solid evidence of any significant shift, or lack thereof, in the Soviet military posture. In other words, we are not certain what information can be taken as evidence of a real shift from an offensive to a defensive Soviet strategy. In a speech before the United Nations General Assembly in December 1988, Gorbachev announced significant unilateral cuts in the number of Soviet forces in Eastern Europe and in the Soviet Union, but military experts still disagree as to the actual military significance of these announcements, in large part because the cuts have not yet actually occurred.

Even more uncertain is the long-term prospect for the success of Gorbachev's perestroika and the impact on Soviet foreign and military policy. We do not understand the relationship between Soviet capabilities and Soviet impulses. Would continuing Soviet economic weakness, for instance, lead to international adventurism or to retreat? Would the success of domestic economic, political, and social restructuring result in greater Soviet maturity or bellicosity?

If the conference discussion provides any indication of the U.S. judgment about these questions, the United States will probably operate, at least in the near to mid-term, on the assumption that the Soviet threat will decline. Still, the political uncertainties about Soviet behavior and goals must temper any prediction about the future of U.S. nuclear weapons and, particularly, about any decline in the roles of those weapons.

Technological Influences

A second session at the conference, opened by John Foster, was concerned with the technological influences on the future of nuclear weapons. Compared to the consensus obtained on policy influences, this session was less definite about the impact of future technology. The lower degree of consensus was true both of nuclear weapons technology itself and of the non-nuclear technologies of weapons guidance and control and weapons delivery systems that might complement or substitute for nuclear weapons missions. There was no clearly identified nuclear "technology imperative" that would substantially increase or decrease the role of nuclear deterrence in U.S. national security policy—although there might be one or two potential imperatives in the wings.

This emphasis differs from the past. During the first twenty-five years of the nuclear era, steady advancement in both nuclear and non-nuclear weapons technologies allowed very significant shifts in fundamental national security policy.

The history of nuclear weapons technology. The earliest nuclear devices were relatively crude affairs, involving large physical assemblies and inefficient use of fissile material, and they produced relatively small yields, or weapons effects. One of the first post-World War II research and development goals was to build physically small fission devices of greater efficiency with more flexibility in yield. Small fission devices resulted in a much wider choice of delivery systems than the strategic bombers required for Little Boy and Fat Man (the weapons used against Japan). Eventually, smaller warheads allowed us to deploy a number of battlefield nuclear systems, such as mines, artillery shells, missile warheads, and gravity bombs. The main deployment area for these tactical nuclear weapons was Europe, where they became a critical element in the adoption by the U.S. of an extended deterrence defense policy for our NATO allies. Also, small fission weapons deployed on short-range missiles became an early form of air defense for U.S. military forces.

A vigorous program to engineer large-yield thermonuclear weapons occurred in parallel with the effort to develop tactical weapons. Because these large-yield strategic weapons were also very large in physical size and mass, they required delivery by large, dedicated bomber aircraft. However, the successful design of such weapons allowed the United States to adopt a strategy of massive retaliation as the principal element of its early deterrence policy.

During the 1960s and 1970s both nuclear and non-nuclear weapons technology continued to develop. In particular, we developed fairly accurate ballistic missiles and medium-yield, medium-size warheads. These warheads were

There are some inventions and needs in the nuclear weapons field that do look attractive from a technical-military point of view:

—penetrating warheads delivered by aircraft or by cruise or ballistic missiles that could penetrate, to one degree or another, into water, ice, and ground;

—directional warheads that focus either mass or energy in a particular direction with extraordinary effectiveness, which could include an x-ray laser capable of delivering intense energy on targets at great distances in space, a nuclear assembly that could deliver solid matter in intense beams preferentially in one direction, or the use of a nuclear explosive to create

intense electromagnetic waves... Unfortunately, it is my perception that the three nuclear weapons laboratories are not leaning into these opportunities as aggressively as they can or as they should. If we do not pursue them aggressively, the laboratories of other nations are likely to do so, perhaps without our knowledge. These nations could then take advantage of new capabilities and put them in the field, at which time we would be at a considerable disadvantage. So I would urge the three laboratories to get together and find ways to pursue these known opportunities more aggressively and competitively, as well as to assign teams of talented, creative individuals to explore new opportunities.

—John S. Foster, Senior Vice President, TRW Corporation and the former Director of Lawrence Livermore National Laboratory, opened the session on technological influences.

deployed on a wider array of aircraft, and they provided an early capability for both air defense and ballistic-missile defense. Further development of small-diameter thermonuclear warheads, coupled with accurately guided ballistic missiles, allowed the U.S. to create a much more survivable deterrent force. Survivability was assured by locating a significant number of the weapons on ICBMs in silos and on long-range submarine-launched ballistic missiles (SLBMs) in submarines, which are extremely difficult to locate and attack. These developments brought about a period of strategic stability, since both the major nuclear powers could back up their deterrence policies by assuring retaliation against any nuclear attack with a triad of strategic forces: bombers, ICBMs, and SLBMs.

This basic strategic stability has endured for a number of years now, but it has not meant that nuclear technology has stood still. Research and development has been devoted to extracting specialized effects from nuclear explosives so that, in some circumstances, they could be used in a more discriminating fashion. One well-known example was the development of a device, popularly known as the neutron bomb, that emphasizes the weapon's radiation output while reducing effects of the blast. Such a technology, for example, makes for a more feasible nuclear defense by NATO against massive armored attacks by the Warsaw Pact. However, political reasons have kept the Alliance from deploying weapons in Europe armed with such enhanced-radiation devices.

For more than two decades now, research and development of nuclear weapons technology has also concentrated on making nuclear weapons increasingly safe and secure to deploy and use operationally. To insure that no terrorist or other unauthorized use of a nuclear weapon occurs, physical and electronic protection systems called

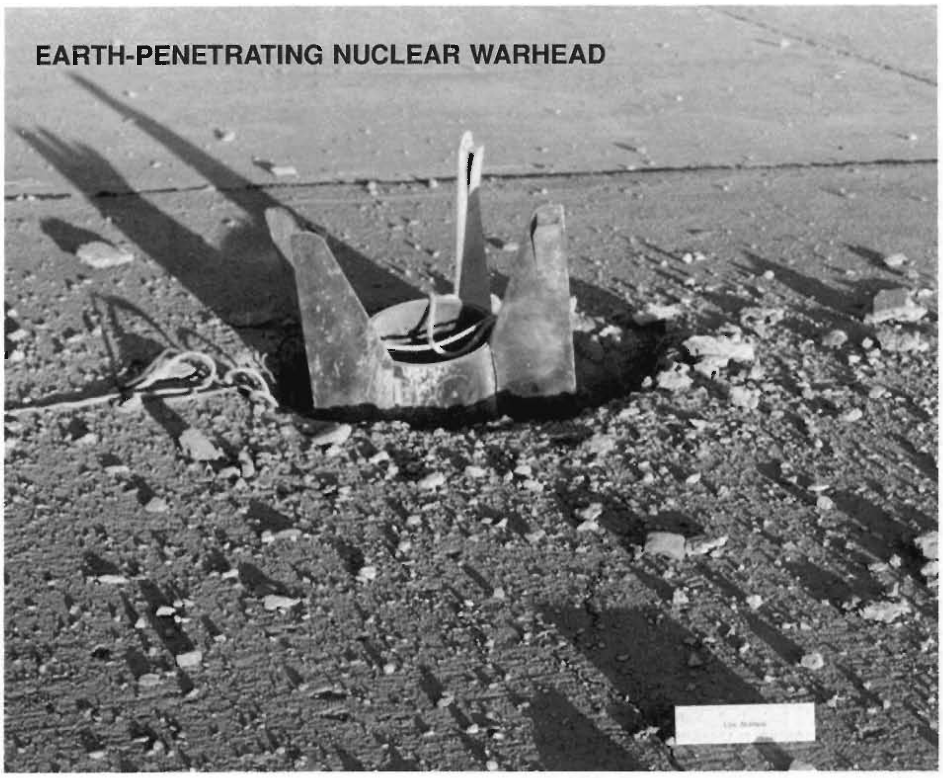


Fig. 3. Test photographs of a warhead designed to penetrate the ground before detonating. In this particular test the warhead penetrated a foot of concrete over hard dirt and came to rest almost nine feet below the top surface. In subsequent tests, an improved warhead penetrated the concrete completely.

permissive action links, or PALS, were developed that require a unique set of instructions from the correct command authority before a nuclear weapon can be used. Other safeguards and security measures have also been developed in recent years, such as warheads designed to insure that they are *one-point safe*, that is, that there is no danger of nuclear explosion even if, for example, they are dropped accidentally.

However, as important as these technology developments have been, they are not the kinds of changes that in turn create key changes in national strategic policy. As mentioned before, the sense of the conference was that no technology development seemed imminent within the field of nuclear weapons per se that would call for fundamental policy shifts. Similarly, no nonnuclear technology development, strategic defenses included, was identified that would alter the fundamental role of nuclear weapons in supporting a policy of deterrence. The feeling was that strategic defenses might alter the form of deterrent relationships but would not destroy them altogether.

The future of nuclear weapons technology. The identification of future technology directions for nuclear weapons development activities included further bolstering of the safety, security, and flexibility of nuclear weapons, thus supporting the requirements that they are safe, survivable, and effective. Three additional areas of research were mentioned that should prove fruitful to pursue in the three-decade time frame examined at the conference.

First, a number of targets in the Soviet Union already assigned to nuclear missions have become increasingly difficult (some might say impossible, in certain cases) to threaten with existing nuclear systems. This difficulty is true for many fixed military targets and for mobile missiles. Also, a number of the emergency command centers for the political and military leadership of the Soviet Union have been moved to sites deep underground, which makes them difficult both to locate and to attack. These trends indicate the utility of a "hard-target kill" capability for nuclear forces, which, if the U.S. elects to pursue the option, will probably be gained through a combination of new warhead designs (Fig. 3) and different delivery systems.

Next, continued work on ways to channel the output of nuclear weapons into forms of directed energy is still useful, particularly for ballistic missile defense or anti-satellite applications. The popular press has focused almost exclusively on the attempts to create a nuclear-driven x-ray laser, but there are other possible ways to use the unique power and energy forms available from nuclear explosions.

The third suggestion is related to the use of special nuclear effects. Military forces, and the civilian societies and economies they are designed to protect, are becoming increasingly dependent upon electronic components. Finding ways to use the effects of nuclear weapons against these capabilities may be an increasingly interesting role for the nuclear weapons research and development community.

An important note here is that while these potential developments in nuclear technology could greatly enhance military effectiveness, they would, at the same time, tend to reduce the survivability of nuclear forces on both sides. Such technological trends work against the emphasis on stability indicated by the political trends.

The past history of nuclear weapons technologies constitutes a steady evolution in capability, military effectiveness, and special-purpose applications. Presently, directed energy is a discontinuity in that evolution and a technology in search of a policy niche. As such, it has the *potential* for making major differences in strategy. In the future we may expect to see further such technological discontinuities emerge. The conference also explored the technological future of other types of military systems. Many of these advances may be dramatic, especially those in the areas of missile and aircraft propulsion, automation, sensors, guidance, C^3I (command, control, communications, and intelligence), stealth, and protection and countermeasures. The overall trend is clearly toward non-nuclear standoff weapons with autonomy, long range, high accuracy, and high lethality; toward C^3I systems with long-range, accurate, all-weather capabilities; and toward computer-assisted decision making for both manned and autonomous systems and command centers. These changes in non-nuclear weapons technologies, over time, will revolutionize the conventional battlefield—a revolution that involves not just a single breakthrough but rather the steady development of many advanced technologies.

Directed energy has the *potential* for making major differences in strategy.

Of particular interest are the non-nuclear weapons that might eventually be substituted in some, if not all, military missions now requiring nuclear weapons. For example, rather than using a nuclear weapon to destroy a large, *fixed* target complex, such as an airfield, extremely accurate guidance and advanced non-nuclear munitions could be used to selectively destroy critical nodes within that complex. However, the technical problems associated with the effective use of long-range conventional systems on *mobile* targets, such as a column of tanks, may remain intractable for decades. Also, advanced conventional weapons will never be able to duplicate the political and psychological effects caused by the sheer destructiveness of nuclear weapons—effects that presumably enhance deterrence. The question of the cost effectiveness of such non-nuclear alternatives to nuclear weapons is also unresolved and may be significant.

Strategic defenses, such as those proposed under President Reagan's SDI program, were not discussed extensively at the conference. This lack of discussion is itself significant, because SDI was initially proposed to change dramatically, and even eliminate, the future requirement for nuclear weapons. The consensus from the discussion that did occur was that strategic defenses, if deployed over the next several decades, will probably not play a leading role in the long-term evolution of U.S. nuclear policy and forces. Rather, any defenses are likely to be limited because they would be intended to enhance a deterrence policy based, as it is today, on the threat of nuclear retaliation.

Thus, technological trends were not seen to have as clear and as significant an impact on future national policy as political trends. This feeling appeared true even for SDI technology and ran counter to the previously strong historical impact of technology on policy.

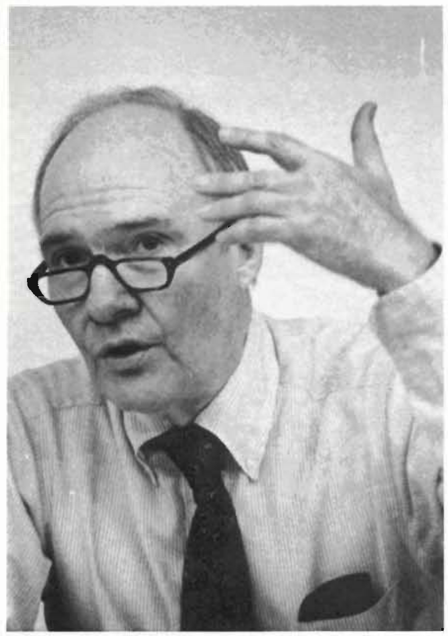
Military Influences

A session opened by Brent Scowcroft dealt with the military influences on the future of nuclear weapons. To under-

Technological trends were not seen to have as clear and as significant an impact on future national policy as political trends.

A new phase in the military evolution of nuclear weapons could be driven by ongoing improvements in weapons system accuracy. Improved guidance holds out the promise of accomplishing the same missions with smaller nuclear weapons so as to avoid collateral effects. It also raises the issue of whether it will be possible to use conventional weapons for some targets that have previously required nuclear weapons ... I certainly agree we should attempt to avoid unnecessary collateral damage, and I think that substituting non-nuclear for nuclear warheads probably has a good deal of utility, especially in the European context. But it is not at all clear that this represents a truly significant development in our views about nuclear weapons and deterrence...

Arms control is likely to have a major military impact on nuclear weapons' requirements. Since about 1950, we have been trying to bolster the credibility of deterrence in Europe. By stationing battlefield weapons in Europe, changing to flexible response, deploying the INF forces, and so on,



our consistent purpose has been to make deterrence as strong as possible. It seems to me, however, that many of the arms control schemes being advanced today have the opposite intent—their purpose is to determine how much we can "shave off" deterrence without getting to the point that it fails. That is my principal complaint about the INF Treaty: not that it is a disaster in itself, but rather that it takes us in the wrong direction.

Arms control reductions may force us to think seriously about how we wish to target the remaining forces. If we really do limit the number of nuclear weapons significantly, we may have to look at targeting from a rather different perspective than we have over the past several decades. The target planners would have to return to first principles and ask themselves what they absolutely must be able to hold at risk to make deterrence as strong as possible—and, if deterrence fails, what they must strike to achieve U.S. objectives.

If both sides continue to develop survivable nuclear force structures, this will also raise similar questions about targeting. For example, the continuing Soviet deployment of mobile, survivable ICBM forces will challenge our traditional notions of counterforce. What do we target then? Are we thrust back to an assured destruction targeting policy? Should we target the Soviet leadership and, if so, at what stage of a conflict? Should we try to separate the leadership from the control of its military forces by attacking the command and control systems? Should we concentrate more on targeting conventional forces, such as army units moving out of garrison? These will be critical issues for at least the next ten to fifteen years, if not beyond.

—Brent Scowcroft, former Chairman, President's Commission on Strategic Forces, opened the session on military influences; he more recently has become Assistant to the President for National Security Affairs.

stand what some of those influences are, one must first understand how the military itself views nuclear weapons.

The American armed forces, quite reasonably, approach the issue of nuclear weapons from a military perspective: how can these weapons assist the military in achieving the peacetime and wartime objectives required of them under American national security policy? Such attributes as effectiveness, flexibility, and, to some extent, discrimination thus rank high when the services consider deploying nuclear weapons systems.

In addition, the particular services have vested institutional interests in maintaining certain types of weapons systems. The Air Force and the Navy devote significant portions of their budgets to what might be called national, or strategic, nuclear forces—the Strategic Air Command (SAC) and the Navy's strategic missile submarine force. Both services are committed to maintaining their "fair share" of those forces, whatever unilateral force structure decisions or arms control agreements the U.S. government might make. Finally, the U.S. military supports nuclear deterrence and the deployment of nuclear weapons because the services have neither the resources nor the plans to fight a massive, global conventional war with the Soviet Union. The Army, in particular, has no interest in fighting a replay of World War II, which might be the only realistic alternative military strategy if nuclear weapons did not exist. U.S. nuclear weapons, by deterring the Soviet Union, eliminate this possibility.

The U.S. military supports nuclear deterrence and the deployment of nuclear weapons because the services have neither the resources nor the plans to fight a massive global conventional war with the Soviet Union.

Over the past thirty years, however, parts of the U.S. military have had difficulties attempting to integrate nuclear weapons into their operational concepts and plans. This is especially true for the tactical (short-range) nuclear weapons. The services—fortunately—have no "real world" experience with nuclear weapons, and they find it difficult to predict the course and outcome of any war in which such weapons are used. The Navy, for instance, is particularly reluctant to plan for any limited nuclear warfare at sea, having concluded that enemy use of nuclear weapons would make traditional surface naval missions impossible to carry out.

What implications do these ambivalent military perspectives—implications which could not be explored fully in the conference—have for the future roles and requirements of nuclear weapons? Judging from the views of the speakers, who were not official representatives of the respective services, some of the implications are the following:

- The U.S. Air Force will likely be interested in maintaining a strategic nuclear force structure very similar to that in place or planned today. This structure is a mix of fixed and mobile ICBMs and of bombers that penetrate enemy territory or that stand off outside the borders and release missiles directed at the targets. The Strategic Air Command will likely attempt to develop a significant non-nuclear role beyond its current nuclear assignment that would use long-range bombers, such as the B-52, to deliver conventional bombs and standoff missiles.
- The U.S. Navy will probably continue to support the deployment of submarine-launched ballistic missile forces but will tend to resist and decrease other nuclear roles that interfere with normal fleet operations. For instance, the shipboard and submarine deployment of tactical nuclear weapons for use at sea makes it very difficult for the Navy to conduct its more traditional missions, such as sea control. The future nuclear role of naval aircraft also remains uncertain.
- The U.S. Army is not likely to change its view of the importance of nuclear weapons as a deterrent over the next several decades. The Army anticipates a decrease in the number of stockpiled nuclear weapons and will likely support significant increases in the military effectiveness of nuclear warheads with the same or better level of discrimination. The Army will have an interest in developing further options for its nuclear artillery systems and will support the modernization of air-carried theater nuclear systems.

The services—fortunately—have no "real world" experience with nuclear weapons, and they find it difficult to predict the course and outcome of any war in which such weapons are used.

The conference discussions begged a critical military (and technical) question that seems to be at the heart of our current strategic uncertainty about nuclear weapons: whether and how to target Soviet nuclear forces? Such targeting is called the *counterforce* mission.

With respect to its long-range nuclear forces, the United States, at present, places highest priority on their counterforce mission. We have already noted the long-term political trends that, in the name of stability, work against a continuation of the counterforce mission, but there are also legitimate military and technical reasons to question the viability of that mission. Soviet nuclear forces are becoming ever more difficult to locate and destroy promptly because they are being made mobile on land and in the air or are being concealed aboard submarines. If the United States continues to target Soviet nuclear forces, it must invest considerable resources to discover and deploy a military-technical solution to this problem.

Any move away from counterforce targeting, whether mandated by political or technical pressures, would represent a significant shift in military emphasis for nuclear weapons. In this case, would the United States be forced to emphasize nuclear roles and requirements based solely on attacking enemy cities? Or are there other missions—for instance, targeting general purpose forces or command and control centers—that might redefine the military effectiveness criteria for long-range nuclear forces? To further complicate the issue, although effective counterforce operations do not appear technically feasible for either side in the foreseeable future of five to fifteen years, such a judgment may not hold over the thirty-year period of this study.

Thus, a certain amount of ambivalence clouds our view of the military trends and influences. In part, this is due to the fact that all forces bearing on the future of nuclear weapons—whether they be of a political, technological, or military nature—are intertwined, the one with the other. Some of the ideas expressed at the conference about how the various facets of this global problem will unwind were controversial. Such controversy was expected and encouraged because, above all, the conference was designed to stimulate the right kinds of questions about the future of nuclear weapons. ■

Further Reading

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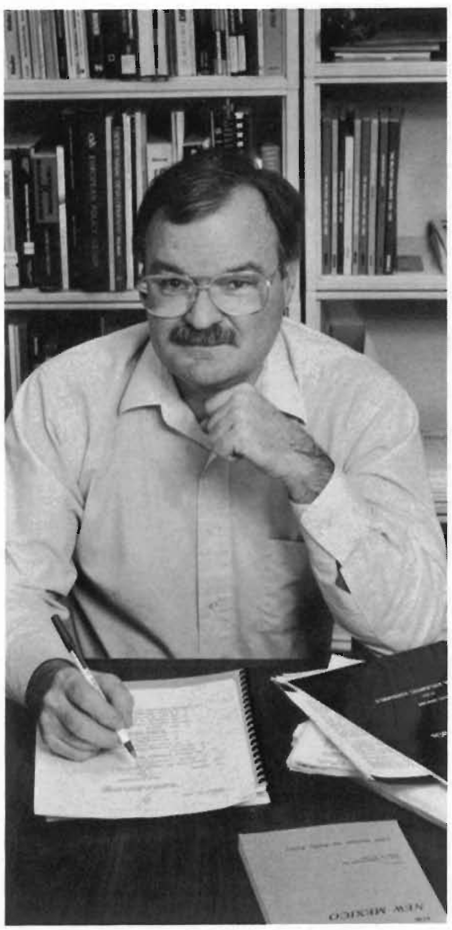
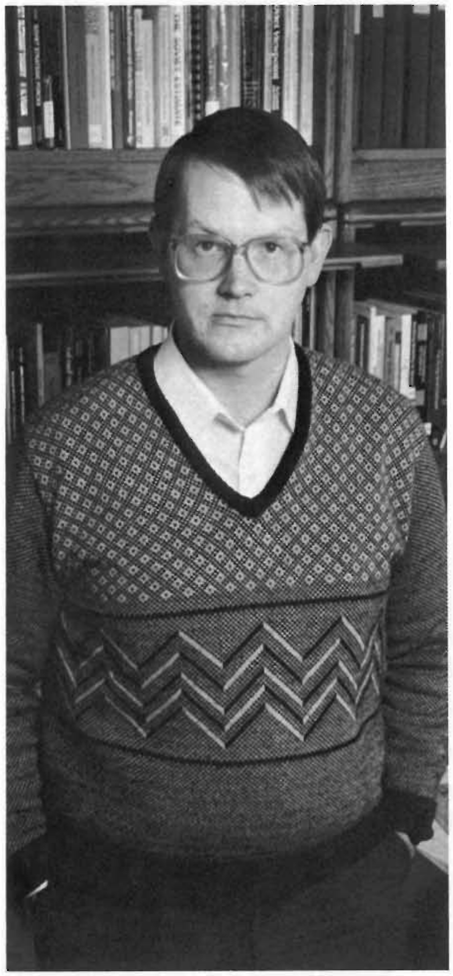
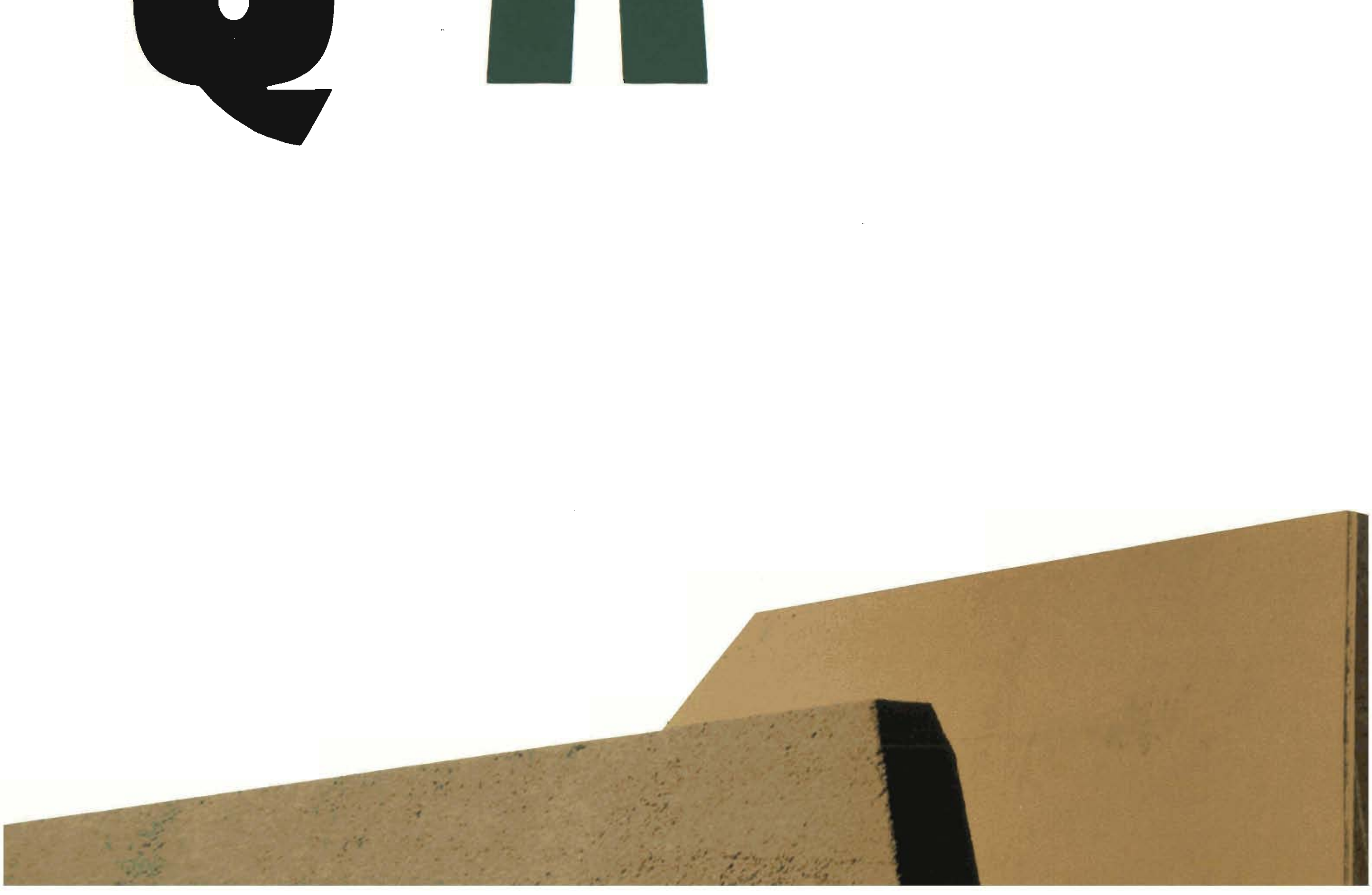
Robert Pendley is Deputy Director of the Center for National Security Studies at Los Alamos and holds a Ph.D. in political science from Northwestern University, as well as degrees in physics from the University of California at Berkeley and the University of Oregon. At Los Alamos he has held staff and program management positions in arms control, verification, and international security policy and has interacted extensively with U.S. government agencies and governments and institutes abroad. His Center responsibilities include formulation and execution of the Center's broad program of analysis and policy research, and his publications include the book *Atoms for Peace*.





Patrick J. Garrity is a staff member in the Center for National Security Studies, where he has been working on U.S. nuclear weapons and arms control policies. He received his B.A. in history and political science from the College of Idaho in 1977 and his Ph.D. in government (international relations) from Claremont Graduate School in 1982. Before joining Los Alamos in 1987, he was a Fellow in National Security Studies at the Center for Strategic and International Studies (1983–1985) and a teaching professor at the Naval Postgraduate School (1985–1987).

Q&A

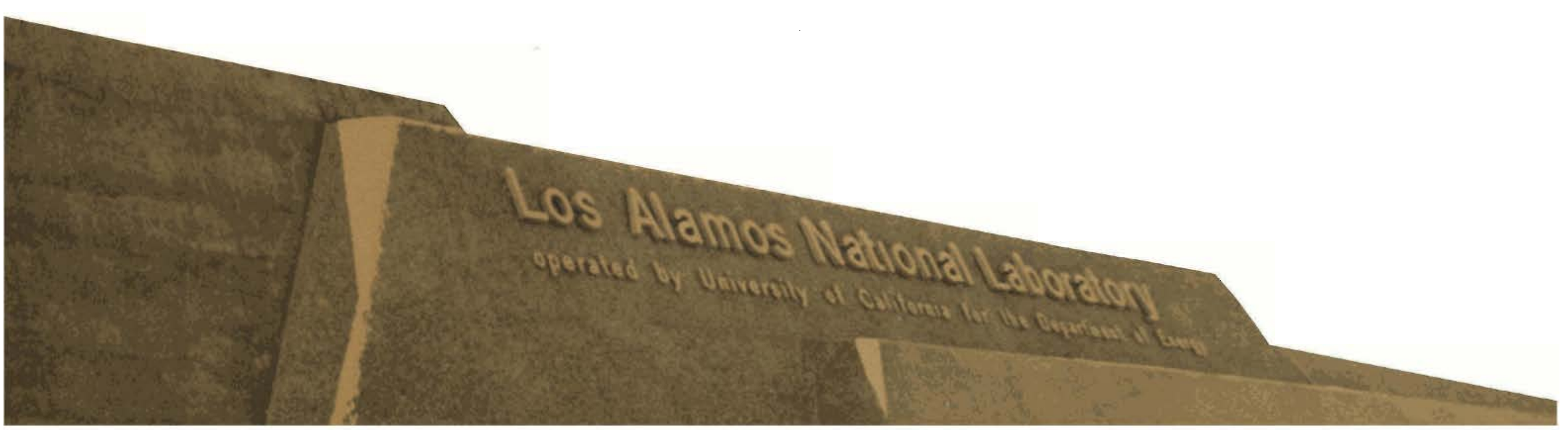


THE FUTURE OF NUCLEAR WEAPONS

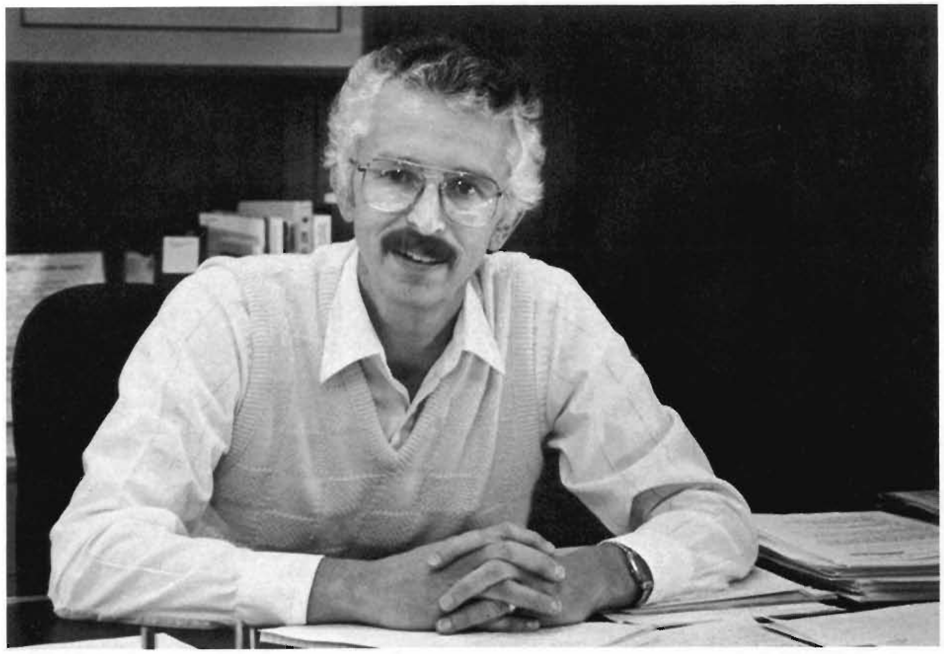
Q *How does a conference on the future of nuclear weapons, a conference that looks forward to potential changes in nuclear weapon requirements, affect your thinking and planning about the future of Los Alamos and the nation's nuclear weapons complex?*

A The primary job of the Laboratory is to provide the technological foundation for a credible nuclear deterrent. Deterrence is a broad and dynamic concept—for one thing, an effective deterrent must be technically viable *and* politically credible.

Experience shows us that maintaining such a deterrent requires frequent technical revisions and adaptations of the nuclear stockpile. These changes meet shifting challenges, including new nuclear weapon missions mandated from time to time by the national leaders. In other words, the Laboratory must not just maintain today's stockpiled weapons but must provide what I call nuclear competence. Competence implies a readiness to meet new challenges, a flexibility to respond in new technical directions, and a far-reaching technological vision that assures the nation won't be caught unprepared by technological surprise. To do this, we must maintain the highest level of scientific and technological excellence in our weapons and basic research programs. Only then can our leaders be confident of our ability to meet our nation's requirements.



But we also know that future nuclear weapons requirements—the requirements that provide technical direction for the weapons program—will depend greatly on developments in national security policy and the politics that surround that policy. The Conference helped us examine that technology-policy interface. It focused attention on the emergence of a world with multiple power centers and brought to the fore many questions about the role of nuclear weapons. We can't predict the future, but the Laboratory must be prepared to face any changes that might occur. Technological developments require long-term planning, a difficult task in the context of a changing political climate. Understanding the important but complex links between the weapons technology on the one hand and the security policy on the other helps our long-term planning for the Laboratory.

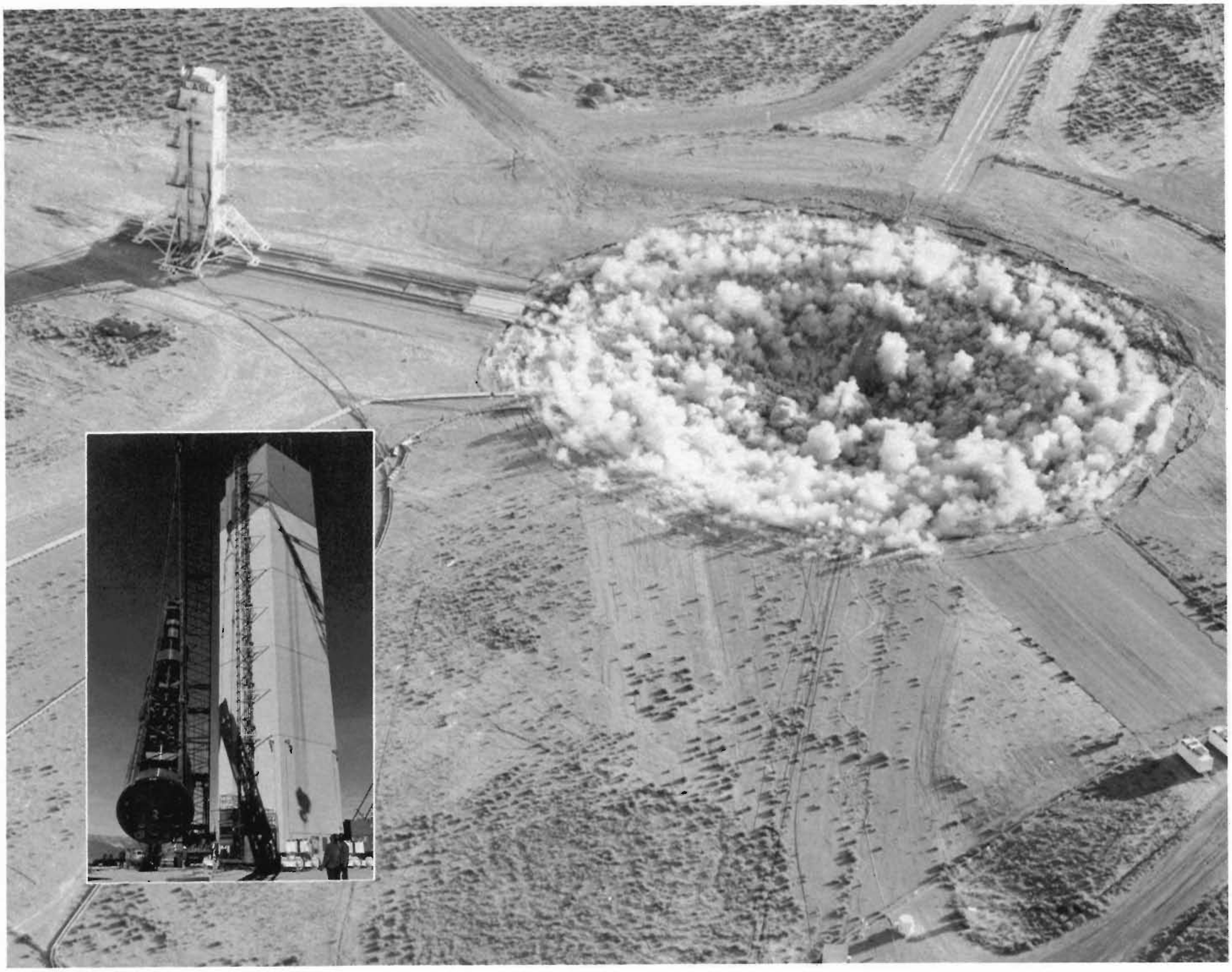


Q *Is nuclear testing an important part of nuclear competence?*

A Nuclear weapons testing is one of the *critical* elements of maintaining a credible nuclear deterrent. Such testing is current U.S. policy, and the reasoning behind it is well known. For example, testing is required if we are to ensure nuclear deterrence in a changing strategic environment. Also, testing assures us of the reliability of the stockpile and allows us to improve the safety and security of nuclear weapons with confidence.

What's sometimes missed in our position regarding the need for testing of nuclear weapons is that it's no different than the position taken by any other high-technology activity—that is, component and product testing are universally considered indispensable. In the auto industry car frames are shaken through millions of cycles of simulated road tests; in the aviation industry wind tunnel tests help shape new designs; in the aerospace industry almost every component is thoroughly tested before being accepted for flight use. The Government, taxpayers, and consumers alike consider it a crime, or, at the very least, a breach of professional ethics, to place untested consumer and industrial products on the market. And although nuclear weapons have important differences from other complex technical systems, the need for testing is fundamentally the same and the impact of error is considerably greater. From a technical perspective it makes sense to depend on nuclear testing for as long as we continue to rely upon our nuclear deterrent for security—especially if nuclear arms are reduced as a result of arms control.

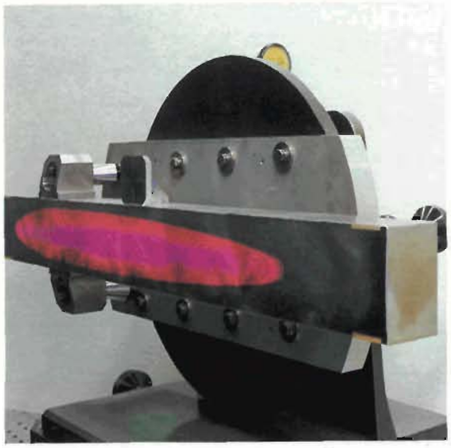
Q *Can't nuclear weapons be developed simply by using our current knowledge of the physics involved? Why do we need to carry out explosive nuclear tests?*

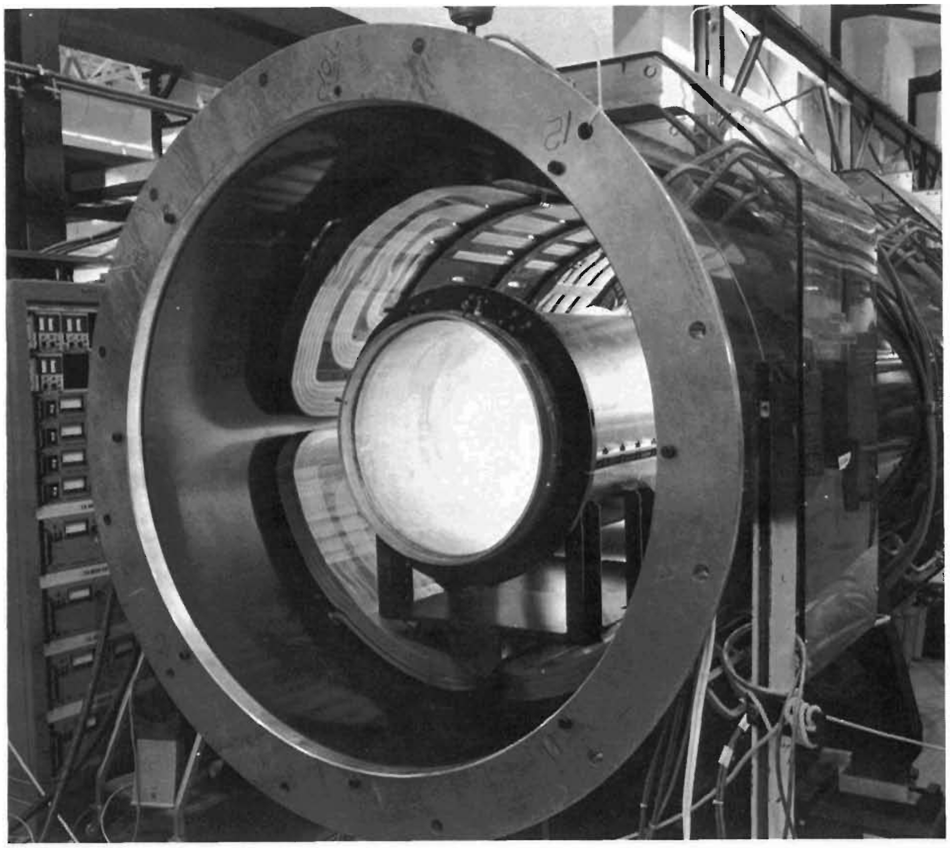


The Nevada Test Site is the location of all U.S. underground nuclear weapons tests. Here, a ring of dust rises as the underground cavity formed by a nuclear explosion collapses. Inset: in preparation for another underground test, this diagnostics rack will be lowered into a bore hole, giving instruments attached to it a line of sight to "ground zero," the location of the nuclear device.

A The events that occur in a nuclear explosion are so complex and insufficiently understood that even today we still cannot design weapons from first principles of physics or from computer simulations alone. Further, nuclear explosions produce temperatures and pressures like those inside a star and cannot be simulated in a laboratory. Thus, we must use an iterative design process involving theory, computer modeling and calculation, non-nuclear laboratory tests, and underground nuclear tests. Ultimately, nuclear tests are essential in calibrating our theoretical design models, which undergo continuous development.

The same holds true for the engineering problems. Nuclear tests provide the





Two research efforts at Los Alamos that could have an impact on directed-energy weapons technology are the neutral particle beam and the free-electron laser. Right: the objective lens of the Laboratory's large-bore magnetic telescope for a neutral particle beam was tested recently at Argonne National Laboratory. Left: grazing reflections, which spread out a beam's "footprint," allow the intense light of a free-electron laser to be redirected without damaging the optic surface of the mirror. The technique, simulated here using the red light of a helium-neon laser, also reduces the effects of mirror aberration and scatter.

final proof of warhead engineering and the packaging of components. The subtle effects of many engineering changes on warhead performance are often more difficult to predict than changes in the physics design.

Q *Then are you opposed to a comprehensive test ban treaty?*

A I have already stated that nuclear testing is critical to maintaining a credible nuclear deterrent. We believe that under a comprehensive test ban our nuclear design and engineering expertise could erode, and erosion could undermine the nation's nuclear competence.

Yet I recognize that there are other considerations in the debate about nuclear weapons. Nuclear testing has taken on great symbolic significance, and some people believe that curtailing testing will end, or at least slow down, the arms race.

In the end the nation's policymakers must look at the trade-offs between potential benefits of increased restraints on nuclear testing and the technical risks and consequent military penalties. Our job is to objectively evaluate the technical risks of further testing restraints.

Q *In most projections nuclear weapons are expected to remain the centerpiece of U.S. deterrent forces, although some experts foresee fewer of them and some narrowing of their role. In that case, how can Los Alamos prevent a decline in the quality of the nuclear weapons science and technology base?*

photo by Jerry Halladay

Advanced techniques and diagnostic capabilities developed for nuclear weapons programs have frequently been adapted for use in a number of other applied technologies, including the design and testing of conventional weapons. Here a warhead developed by Physics International is being dynamically tested using the Laboratory's high-speed, monorail rocket sled. After having been accelerated along the track from left to right, the warhead detonates at the target, which, in this case, is "projected 1995 Soviet armor." Surrounding the target area are a variety of diagnostic instruments, including intense x-ray machines that record the interaction of the warhead with the target (see "ATAC and the Armor/Anti-Armor Program" and "Studying Ceramic Armor with PHERMEX").

A First, I think we have to keep in mind that even in the midst of the current enthusiasm for reducing nuclear weaponry, nuclear deterrence remains a critical element of our defense posture. Even if the number of U.S. nuclear warheads were substantially reduced, there would still be a continued need for significant research and development at the nuclear weapons laboratories. Smaller nuclear stockpiles that continue to support deterrence would likely require changes in the *kinds* of weapons as well as changes in nuclear designs.

Furthermore, the size and the diversity of the current stockpile provide some insurance against both surprise attack and the sudden emergence of unforeseen technologies by another nation. If large numbers of nuclear weapons are eliminated, the weapons laboratories will be continually called upon to assure the survivability and technical robustness of the remaining stockpile. We must also continue to inform the nation of technological possibilities on the horizon that we may be forced to defend against.

We seek to complement our direct nuclear weapons programs with other kinds of scientific and engineering research that will help us remain at the cutting edge of scientific knowledge. We strive to maintain a world-class scientific institution staffed with some of the best professionals in the nation. In this way we will continue to serve a vital national function by retaining our ability to solve large, complex scientific and engineering problems. In the past the base of nuclear weapons science and technology at Los Alamos has given rise to numerous nonweapon technologies; in the future we will count on challenging programs at the forefront of research and development to help maintain the knowledge and personnel base required to assure nuclear competence.

Along these lines I would point out that about one-fourth of the current Laboratory budget is spent on research for imaginative and powerful non-nuclear defense concepts, including the neutral particle beam and the free-electron laser. Another one-fourth of our effort is directed toward fundamental research in areas such as high-temperature superconductors, supercomputing, mapping the human genome, and in energy and other civilian technologies. These scientific programs may not only have tremendous long-term payoffs to the nation, but they contribute to the Lab's expanding scientific and technical base and form a natural part of the Laboratory's mission—to offer creative solutions to problems of national urgency. These ef-

The Soviet and U.S. flags flying from a derrick at the Soviet's underground test site at Semipalatinsk symbolize the milestone reached when scientists of both countries participated in joint verification experiments at their respective underground nuclear test sites. These experiments allowed both groups to calibrate their detection techniques against controlled, baseline events. The effort does much to ensure that either country can verify compliance with nuclear test treaties by the other.

forts are in support of our attempts to broaden our concept of national security to include economic strength and energy security.

Q *Some policy and technology development trends seem to be going in different directions. Is there any conflict here? For example, why is Los Alamos developing technologies such as the earth-penetrating warhead when we are trying to negotiate reductions in nuclear arms?*

A The long-term trend appears to be toward reduced nuclear arms. But in the short term there are well-recognized deficiencies developing in our deterrent posture that may require new technologies or concepts. For example, our military planners are becoming increasingly concerned about our ability to hold at risk a number of high-value Soviet targets, such as mobile missiles and deeply buried or super-hard structures. The earth-penetrating warhead and other Laboratory weapons concepts provide technical options to U.S. military planners.

But the issue is more general than that specific example. Long-term trends in nuclear weaponry may very well result in different technical requirements in the future, and we must be able to meet them. For instance, improvements in the safety and security of nuclear weapons are clearly desirable, regardless of the size of the nuclear arsenal. Improvements of this kind are made possible by research and development. Finally, we need to build a technology hedge—a hedge against breakthroughs in weapons technology that could place the nation's deterrent at risk. Such breakthroughs would have a greater impact in an environment of significantly fewer weapons.

Q *There was a suggestion at the Conference that over time advanced conventional weapons may play an increasing role in the U.S. deterrent. What would be the implications for Los Alamos?*

A The Laboratory is already contributing very significantly to conventional weapons. This year we are conducting over $200 million in research on non-nuclear technologies that include concepts that may be truly revolutionary, such as particle beams, lasers, and high-powered microwaves. We are also involved in more evolutionary technologies, such as those pertinent to the armor/anti-armor balance of tank warfare. In this case we are using diagnostic capabilities and other advanced techniques developed in the nuclear weapons program to assess the effectiveness of a broad variety of applied technologies.

Although the Lab plans a vigorous program of activities in conventional weapons, we are not assuming that these technologies will replace nuclear weapons. Rather it is our view that they will be used to augment and complement nuclear deterrent forces. There is considerable controversy whether even extremely accurate conventional weapons, including the so-called zero-CEP weapons, can *ever* serve as an effective deterrent by themselves. Not only are there some military missions that can only be accomplished with nuclear weapons, but non-nuclear strategic weapons lack the psychological impact, and thus the full deterrent effect, of nuclear weapons. Accurate conventional weapons can serve as effective complements to nuclear weapons, providing a greater range of conventional alternatives before nuclear use must be contemplated.

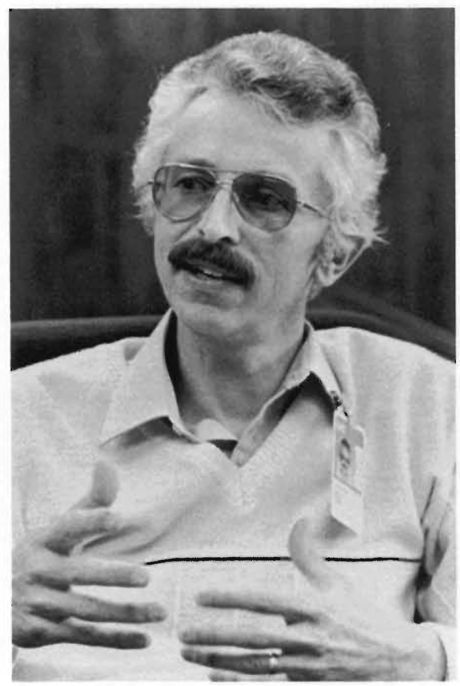
Q *The nation faces a major problem in cleaning up and modernizing the nuclear weapons production complex. Can we do that and still maintain the technology base at the Laboratory?*

A The cleanup and modernization of the Department of Energy weapons production complex is one of the exceptionally difficult problems facing the new administration. Everyone recognizes that the situation is unacceptable now and that we must single out the worst problems and attack them head-on. This effort is going to require the commitment of new financial and technical resources if it's to succeed. We think the Laboratory can play a significant role in the development and application of advanced technologies that may efficiently, and at reduced overall cost, assist with the cleanup. In other words, the bulldozer-and-asphalt approach won't work, and it's too costly. We have to do "smart" cleanup with advanced technologies.

The Laboratory can also help design a modern production complex that will be both more reliable and environmentally benign. Many of the applicable technologies are spinoffs from the Lab's weapons technology base. The important considerations of environment, health, safety, security, safeguards, and materials accountability have to be integrated into process and plant design, not added sequentially in layers. The laboratories can help.

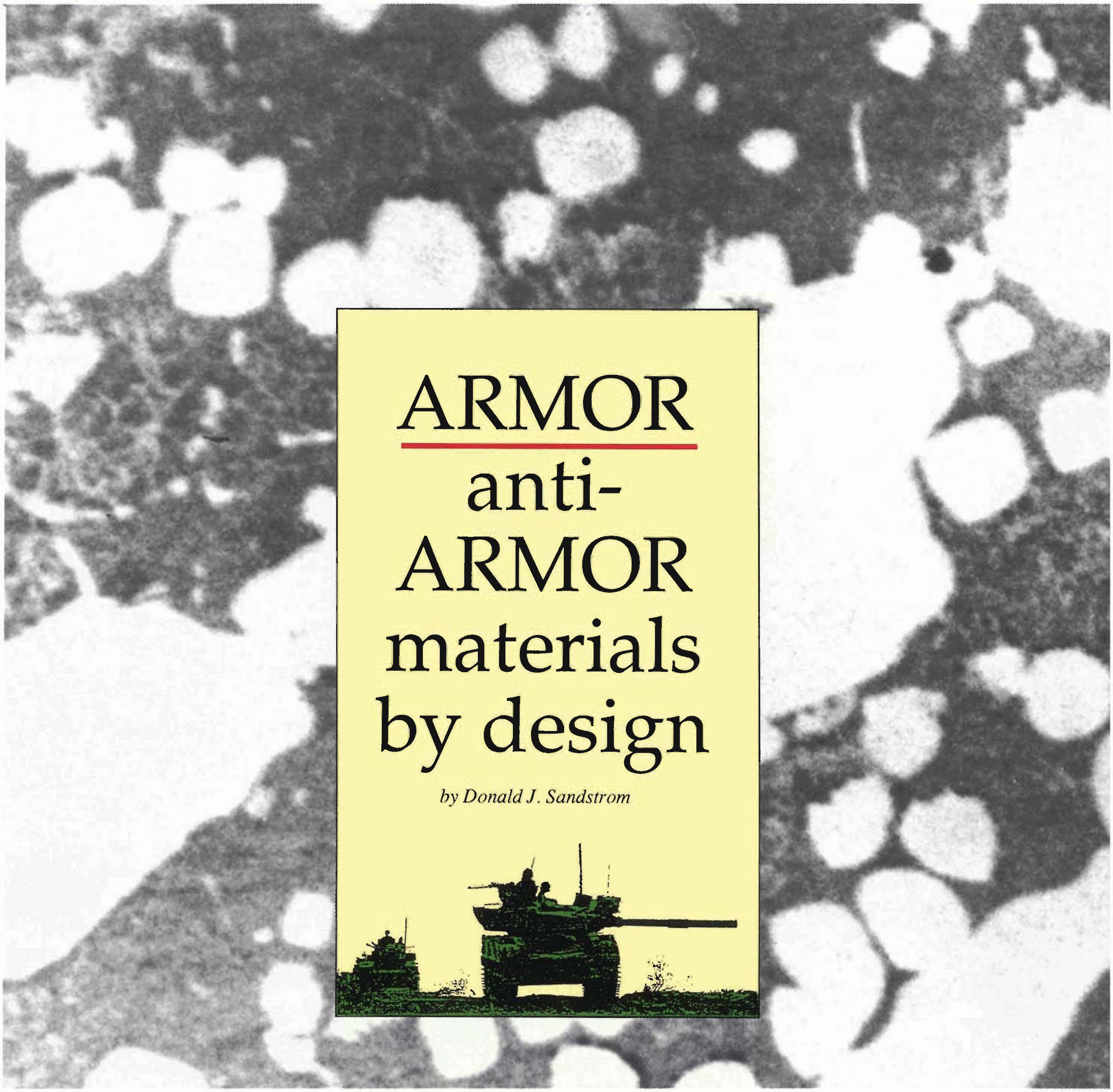
Q *What is the single most important contribution that Los Alamos can make to the nation's security in the future?*

A Los Alamos and the other weapons laboratories are themselves a critical part of this nation's ability to deter war. A policy of mutual deterrence depends upon the belief of national leaders, beyond a reasonable doubt, that their own and their adversaries' nuclear forces are survivable, are deliverable, and will function as intended. This belief does not rest upon the technical knowledge of our national leaders but upon assurances those leaders receive from scientists and engineers and upon the credibility that the scientists and engineers have with their leaders. Unlike non-nuclear weapons—which have a technical base of a thousand or so defense contractors, almost one hundred service laboratories and many universities—the nuclear weapons technology base and the resulting competence rests principally with the three Department of Energy weapons labs. Their combined technical expertise forms the backbone of nuclear deterrence as it evolves over time, regardless of the specific policies or technical directions the nation might choose. ■



ARMOR anti-ARMOR materials by design

by Donald J. Sandstrom



Imagine tank armor that chews up a high-velocity projectile on impact ... or composites of tungsten and uranium that lend an antitank penetrator rod the stiffness of the tungsten, the density and pyrophoric property of the uranium, and the surprising strength of their mixture ... or tiny crystal grains aligned in a sheet of uranium that allow it to stretch into a long, lethal jet of unbroken metal. These examples illustrate how Los Alamos is using its knowledge of materials to design and fabricate new and stronger components for both armor and penetrators of armor.

Our interest in applying ma-

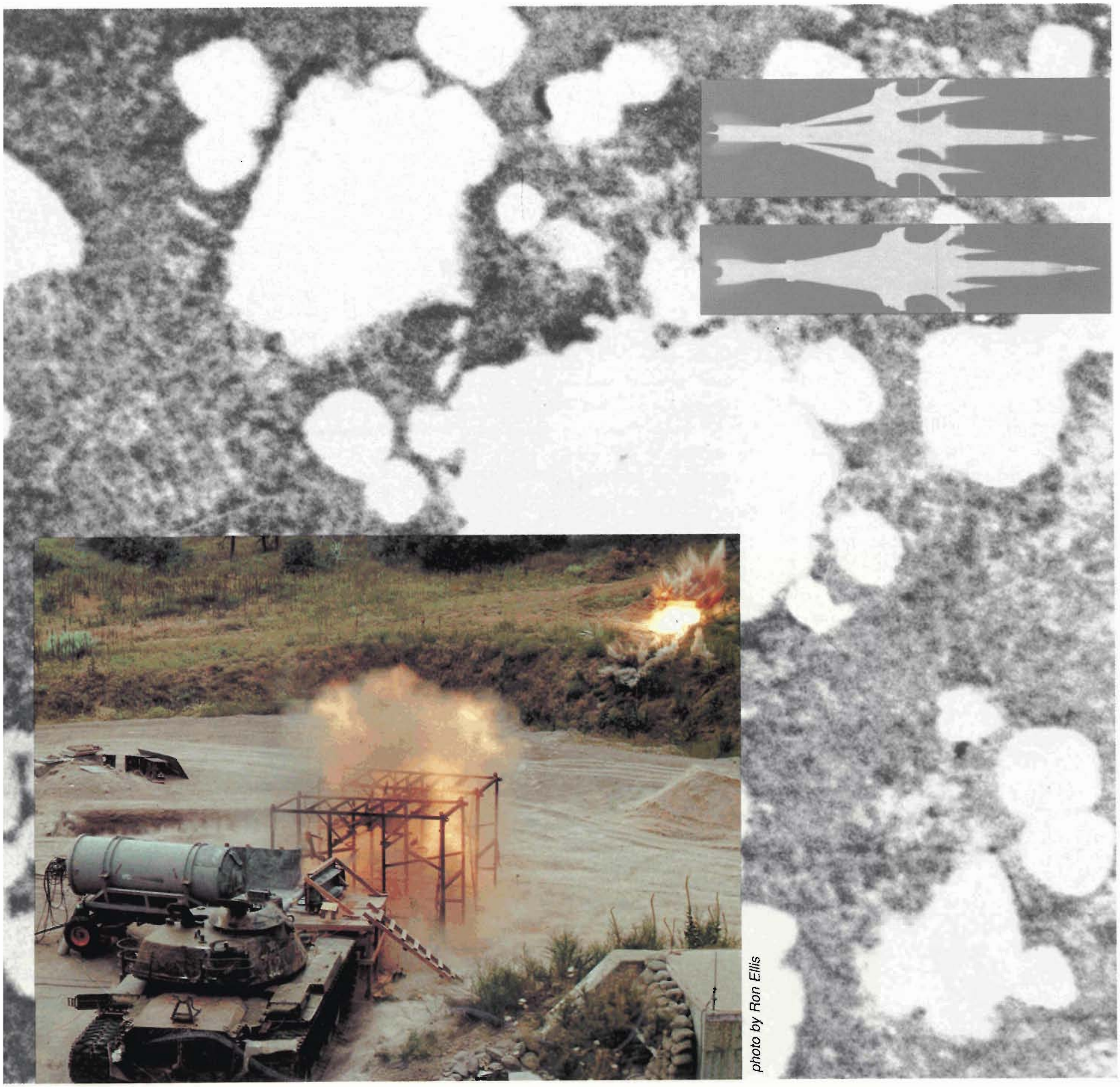


photo by Ron Ellis

terials research to conventional weapons has its origins in the Laboratory's nuclear weapons program. To deal with the unique materials used in nuclear weapons, such as actinides, special ceramics, polymers, and so forth, the Laboratory had to develop significant expertise in materials research. Further, the iterative process of theory, design, fabrication, and testing used to develop nuclear weapons serves as the basis for a similar process in developing conventional ordnance. The attention to detail in material properties required for nuclear weapons is, perhaps, even more important for conventional weapons.

There is also a complementarity between the applications of materials in conventional and nuclear weapons—one that has a synergistic effect on both programs. A nuclear weapon releases so much energy so rapidly that materials behave much like isotropic fluids and can usually be described by hydrodynamic equations. In addition, the performance of a nuclear device is more dependent on the nuclear and atomic properties of its constituents than on material properties. In contrast, a conventional munition subjects materials to less severe deformation rates, and the deformation processes are more dependent on the chemistry and prior fabrication history of its constituents. For example, the behavior of an armor-piercing projectile is strongly affected by variations in the chemical composition, processing history, microstructure, and mechanical properties of the materials from which it was formed.

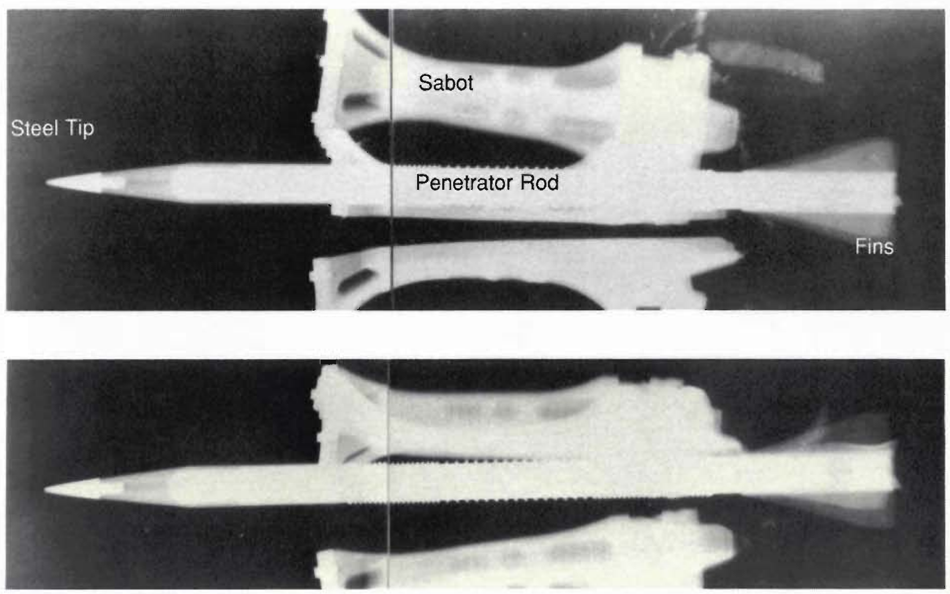
Further, nuclear reaction times are extremely short, whereas the reaction times for conventional munitions are of the order of microseconds—sufficiently long to allow for many types of measurements. And generally, very little, if any, material is recoverable from a test of a nuclear weapon, whereas a test of a conventional weapon frequently leaves a considerable amount of material for post-mortem analysis.

The philosophy underlying the design of nuclear weapons at Los Alamos is traditionally conservative (in the most positive sense), especially in regard to reliability and ease of production. Our approach to conventional weapons follows the same philosophy and pays the same close attention to detail. We strive to use well-characterized, well-understood starting materials, we carefully control the synthesis and manufacturing processes, and we work to develop a complete understanding of the experimental results. Only in this way are we able to relate the performance of armor and anti-armor systems to slight and often subtle variations in material properties or device design and fabrication. I will point out many of those subtleties as I discuss advances made at Los Alamos in the design of armor penetrators and armor, including some surprising properties of a new type of ceramic armor.

A KINETIC-ENERGY PENETRATOR

Fig. 1. These x-ray pictures are orthogonal views of the U. S. Army's M-833 standard round (a fin-stabilized, sabot-discarding projectile for tanks) taken after the round had traveled about two and a half meters from the muzzle of the tank gun. The central rod, or core, is a kinetic-energy penetrator made from a dense, hard alloy of depleted uranium and titanium, and the tip is hardened steel. The sabot is a device that allows the pressure of the expanding gas from the burning propellant to accelerate the core and sabot assembly out the barrel of the gun. The sabot is discarded after the core exits. These pictures show the beginning of the sabot-core separation. Also, note that the lower view reveals a bent fin on the core.

Two Orthogonal Views



Kinetic-Energy Penetrators

Weapons designed to penetrate armor generally fall into two classes: *kinetic-energy penetrators* and *chemical-energy penetrators*. I will discuss the first class now and return to the second later.

A kinetic-energy penetrator is a solid projectile, usually fired from a gun, that uses high-velocity impact (typically, at about 1 to 2 kilometers per second) to defeat the armor. Examples range from the simple spin-stabilized slug of a 30-mm cannon to fin-stabilized projectiles that consist of a long, steel-tipped penetrator rod and a sabot that falls free of the penetrator after it is fired (Fig. 1). If the material strength and kinetic energy of the projectile are sufficient, it penetrates the armor. In addition, the shock wave generated by the impact may travel through the armor plate and blow off a portion of its backside. Fragments both from this *spall* and from the penetrator itself can cause considerable damage to people and equipment behind the armor.

Depleted uranium. Materials research has made particularly noteworthy contributions to the design and development of the kinetic-energy penetrator. The most effective armor-piercing material to date is an alloy developed at Los Alamos—an alloy of depleted uranium (most of the fissionable isotope has been removed) and a small amount of titanium (0.75 per cent).

Depleted uranium was considered an attractive material for kinetic-energy penetrators for a number of reasons. Its high density (almost twice that of steel) makes it easy to produce a penetrator that delivers high momentum and kinetic energy to a small volume of target armor. Uranium is highly pyrophoric, and its impact against steel targets at velocities as low as 30 meters per second produces burning fragments that can ignite fuel or propellants. In addition, depleted uranium is readily available in large quantities and is considerably cheaper than alternative materials.

Uranium, however, is more reactive than most other penetrator materials, and its reactivity can result in corrosion problems, particularly in moist air. In addition, some uranium alloys are susceptible to delayed cracking due to residual stresses induced by fabrication and heat treatment of the rods. The cracking can be avoided if care is taken in the heat treatment to reduce such stresses and to reduce entrapped hydrogen gas to levels less than a few parts per million.

Extensive testing at Los Alamos of uranium alloyed with various metals at different concentrations and processed in a number of ways showed that the alloy with 0.75 per cent titanium had the best combination of properties. The alloy has both reasonable corrosion resistance and high penetration effectiveness. It can be heat-treated easily (by water-quenching and subsequent aging in a high-vacuum furnace) to eliminate the cracking problem, and its properties are not sensitive to precise composition. These last two features help give the alloy low manufacturing costs.

The alloy was originally developed and evaluated at Los Alamos for the U.S. Air Force's GAU-8 system, a 30-mm gatling gun system mounted on the A-10 close support aircraft. The gun can fire a thousand armor-piercing penetrator rounds per minute and is said to be the most effective antitank system in the world. The uranium-titanium alloy was so successful that it has been adopted as the standard for large-caliber penetrators (such as the one shown in Fig. 1).

Dynamic Deformation and Fracture

The penetrating ability of armor-piercing rounds improves with the hardness and strength of the material used. Mechanical properties of this nature are normally determined from the *stress-strain curve* for that material (Fig. 2). Stress is the force per unit area applied to a sample, and strain is the relative deformation of the sample as a result of that stress. Various kinds of deformation can occur (elongation, compression, bending, etc.) depending on the nature of the applied force. If stress to the material is kept below the so-called *yield point*, or proportional limit, the material will spring back to its original undeformed state—in other words, the response is *elastic*. Once this yield strength has been exceeded, however, *plastic flow* occurs, and the material remains permanently deformed. The slope of the initial elastic region, called the *elastic modulus*, is a measure of the material's stiffness; the slope of the later inelastic region is a measure of *work hardening* (since it is the amount of stress needed to achieve a given amount of plastic flow).

Generally, it is desirable for a penetrator to have a high elastic modulus (high stiffness), high yield strength, and high work hardening. For instance, any energy lost to plastic flow in the penetrator is unavailable for destruction of

STRESS-STRAIN CURVE

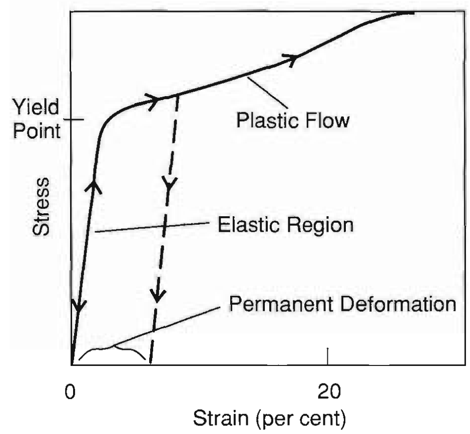


Fig. 2. Many material properties, such as hardness and strength, are determined from the relationship between stress (the force per unit area applied to the material) and strain (the resulting deformation of the material). The initial, approximately linear part of a stress-strain curve is called the *elastic region* because material stressed in this region will not suffer any permanent deformation when the stress is relaxed (in other words, the stress-strain curve returns to the origin). The point at which the curve leaves the elastic region by bending toward the horizontal indicates the onset of permanent deformation and is a measure of the material's *yield strength.* Beyond that point is the inelastic, or *plastic-flow,* region of the curve. The slope of the curve in the elastic region is the *elastic modulus*, a measure of the material's stiffness. The slope in the plastic-flow region is a measure of *work hardening* since a steeper slope means more stress must be applied to create a given amount of deformation.

the armor. Similar considerations are also true of armor materials.

The values of these material properties, however, depend on the *rate* at which the material is strained, and realistic analyses of armor-penetrator impact require knowing both static and dynamic material properties. Static properties are easily measurable. Moreover, they can serve as a starting point for an analysis of the material since dynamic properties often scale in the same direction as the static properties. Nevertheless, it is the dynamic deformation and failure processes that are of paramount interest, and these can only be understood by measuring properties at high strain rates.

The Materials Science and Technology Impact Facility at Los Alamos includes a wide variety of test equipment for determining material properties over a broad range of extreme conditions. Several gas guns are used for high-velocity impact research, and two split Hopkinson pressure bars (Fig. 3), measure the stress-strain behavior of materials at strain rates up to 10^4 per second.

Figure 4 is illustrative of the influence of strain rate on the strength and behavior of a material—in this case, of depleted uranium. Comparing the high (dynamic) and low (static) strain-rate curves of Fig. 4 shows that at high strain rates the material has significantly higher yield strength and higher *initial* work hardening. But as strain increases the material thermally softens—the slope of the curve, in this case, actually becomes negative. Such factors, of course, must be well characterized if one is to fully understand the performance of a material during ballistic impact.

Shock waves. Another factor of great interest for the design of armor and penetrators is the response of materials to imposed shock. It turns out that shock waves generated by the ballistic im-

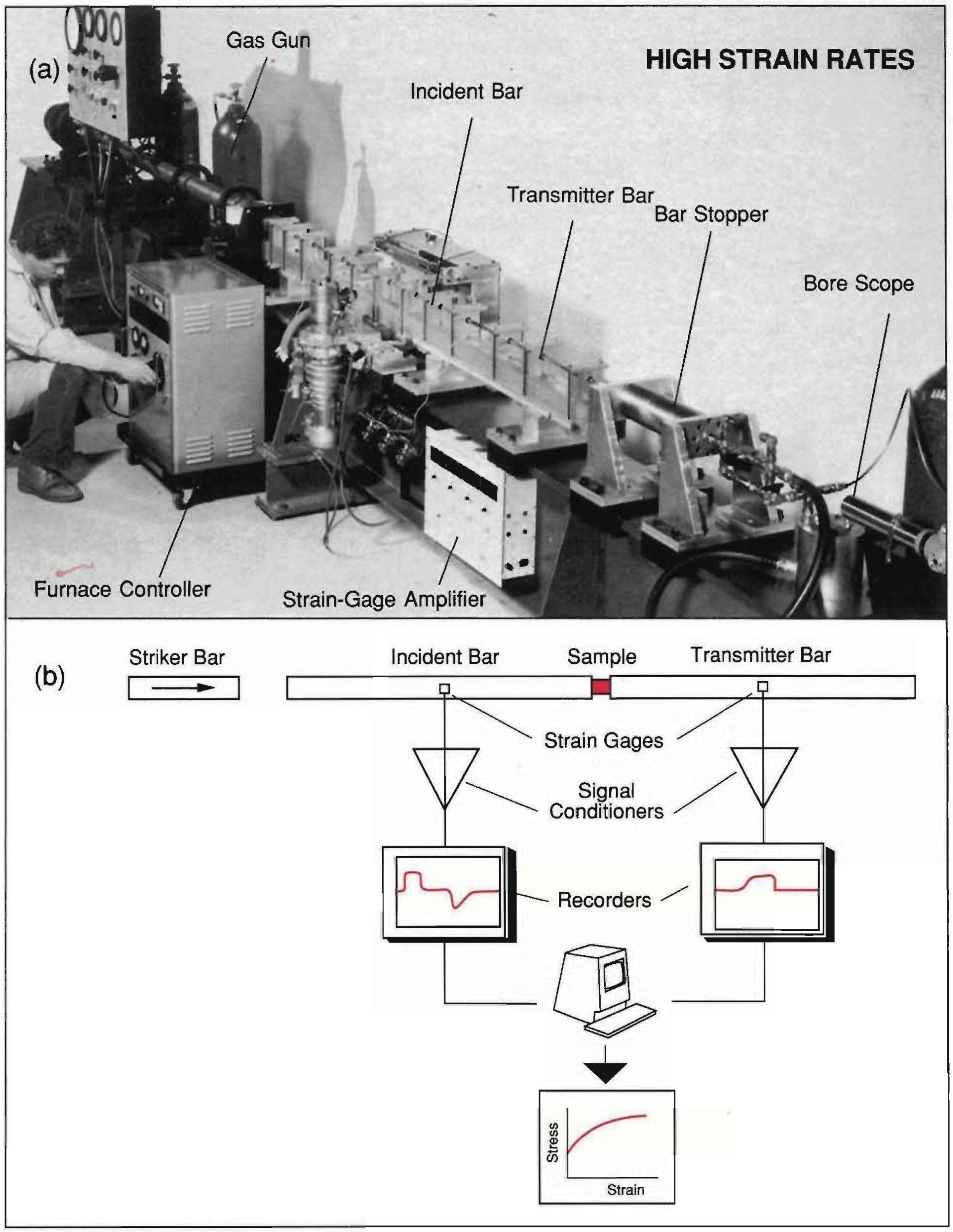


Fig. 3. (a) The split Hopkinson pressure bar can measure the stress-strain behavior of materials up to strain rates of about 10^4 per second. Such measurements are performed, as shown schematically in (b), by placing the sample between two pressure bars made from high-strength steel, then firing a striker from the gas gun on the left. The impact of the striker with the incident bar generates an elastic compression wave that travels into the sample, causing plastic deformation of the softer material. A strain gage in the incident bar measures the strain due to the incident and reflected waves, and another gage in the transmitter bar measures strain due to the wave that passed through the sample. These measurements are used to calculate the strain rate within the sample and the stress-strain curve, such as the one show in red in Fig. 4. This Hopkinson bar facility is unique in that it can test samples at temperatures as high as 1000°C.

DYNAMIC VERSUS STATIC

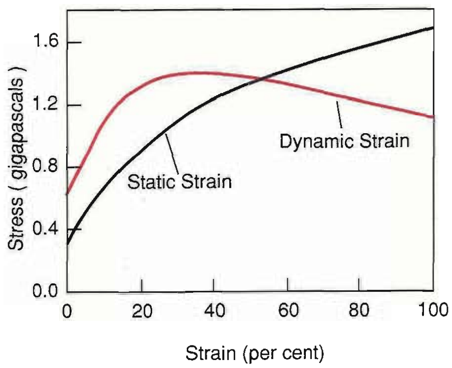


Fig. 4. Stress-strain curves for depleted uranium at strain rates of 5000 (red) and 0.001 per second (black). The dynamic, or high-strain-rate, curve shows a higher yield point and, initially, higher work hardening, followed by lower work hardening as the material thermally softens. As such, the curve illustrates the influence of strain rate on the strength and behavior of the material. Both samples were initially at room temperature (300 kelvins), but the dynamically deformed specimen reached a temperature of 470 kelvins at 100 per cent strain.

pact affect the microstructure and the strength of the components—that is, the "as fabricated" properties of the materials are altered by the passage of the shock waves. The massive structural deformations that occur during armor penetration take place in *shock-deformed* material with transformed properties.

To study those changes, we use an 80-mm-diameter gas gun (Fig. 5) to shoot a projectile called a flyer plate at a target of the same material. After impact the shock-deformed sample is recovered, examined for microstructural changes with a transmission electron microscope, and tested for changes in material properties.

Figure 6 displays static stress-strain curves for an aluminum alloy in its as-received state and after being shock deformed at 2, 8, and 13 gigapascals. All four curves were measured using a slow strain rate (0.001 per second). The data show that yield strength increases with increasing shock deformation, but work hardening decreases. By the time the sample has been strained 20 per cent, the decrease in work hardening has compensated for the higher yield strength, and the curves for as-received and shock-deformed material intersect.

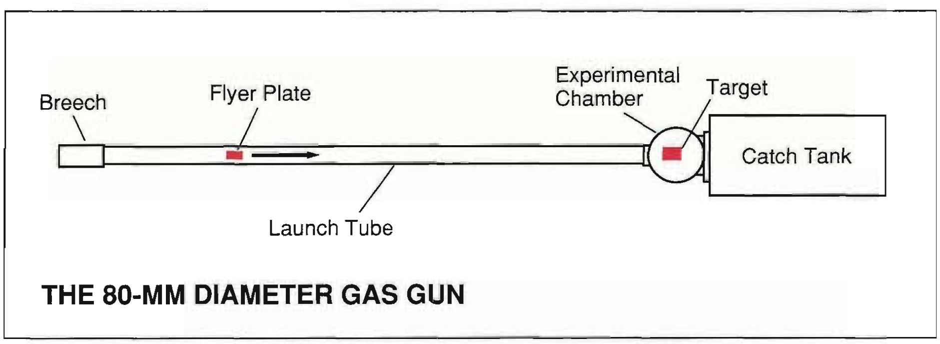
As it turns out, the effect of shock deformation on this alloy is relatively small. Other materials, such as uranium and copper, show much larger changes in their stress-strain curves. In general, we find some materials are very rate and shock sensitive, whereas others are not. Shock-induced changes to materials properties illustrate why it is important to characterize materials carefully and thoroughly.

Dynamic fracture. Fracture at high strain rates is another important consideration in armor and anti-armor performance. Although fracture is generally detrimental to penetrators, certain types of armor may, in fact, turn fracture to an advantage.

Because dynamic fracture is a complex process dependent on structure, processing history, strain rate, and stress state, it cannot be fully characterized by a single parameter or measurement. Our approach to a more fundamental understanding is a combined experimental and theoretical effort based on computer modeling. We incorporate into the models the factors influencing dynamic fracture, and then compare code predictions of deformation and fracture with those that actually occur during armor penetration (see "Modeling Armor Penetration").

We are currently studying the dynamics of how voids are initiated, how they grow, and how the generation of such voids leads to ductile fracture—for example, spall failure in armor plate. Using the 80-mm-diameter gas gun, the spall strength of a material can be determined from axial stress (measured by noting changes in the resistance of manganin gages embedded in the back of the target) or from particle motion at the back surface of the target (by measuring Doppler shifts with a recently installed laser interferometer). Several metals have been studied, including copper, rolled homogeneous armor, and carbon steel. Now that we have mastered the experimental techniques, an investigation of dynamic brittle fracture in ceramic materials is under way.

Fig. 5. One of the test devices of the Materials Science and Technology Impact Facility at Los Alamos, an 80-mm-diameter, single-stage, gas gun. In this gun, pressurized gas shoots a projectile, or flyer plate, down the launch tube at a stationary target in the experimental chamber. The flyer plate and target are typically made of the same material, which is the material being tested for changes due to imposed shock.



SHOCK-DEFORMED ALUMINUM

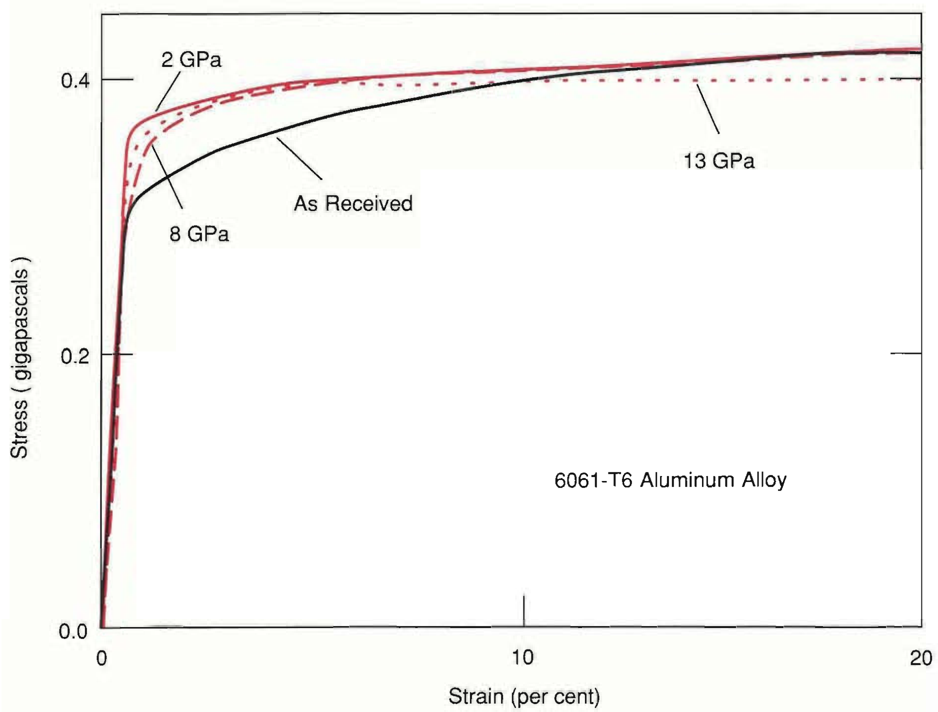


Fig. 6. The static stress-strain curves of 6061-T6 aluminum alloy as received (black) and after having been shock-deformed (red) at 2, 8, and 13 gigapascals with the gas gun in Fig. 5. The shock-deformed samples show higher yield strengths but less work hardening. The strain rate for all samples was 0.001 per second.

One of our main goals in the work on dynamic processes is to develop constitutive relations that describe the stress-strain behavior of materials over a wide range of strain rates, strains, and temperatures. Such relations will increase our ability to predict the behavior of particular systems at a variety of conditions.

As an example, to model deformation and plastic flow we need relations for yield stress and work hardening. The yield stress σ_Y at any instant can be described by using an equation of the form

$$\sigma_Y = s(\dot{\epsilon}, T, p)\hat{\sigma},$$

where s is a function of strain rate $\dot{\epsilon}$, temperature T, and pressure p and $\hat{\sigma}$ is a parameter (or combination of parameters) that represents the current state of the material. This equation reflects the fact that a material's yield stress *changes*, both because of what is happening to the sample (s) and because of the state of the material ($\hat{\sigma}$), which can have been affected, say, by the previous history of stress loading.

We can then go further by describing work hardening $d\hat{\sigma}/d\epsilon$ with an equation of the form

$$\frac{d\hat{\sigma}}{d\epsilon} = \theta_0 \left[1 - F\left(\frac{\sigma_Y}{\hat{\sigma}_s(\dot{\epsilon}, T)}\right)\right],$$

where θ_0 is an initial work-hardening rate and F is a function of the ratio of the current yield stress to a *saturation* value $\hat{\sigma}_s$ that would be obtained by considerable working of the material at a particular strain rate and temperature. In other words, the slope of the stress-strain curve beyond the yield point depends, among other things, on the current stress history of the sample compared to a state in which further stress loading of a particular type has no effect.

The advantage of the above type of analysis is that the kinetics of work hardening are separated from the conditions that determine the yield stress for a given state. This procedure allows predictions for complex strain-rate and temperature histories, such as are typically found in dynamic impact events. We have developed constitutive relations for model metals and are now extending this work to armor and penetrator materials.

Composite Penetrators

The Department of Defense has a need for gun-launched kinetic-energy penetrators with length-to-diameter ratios sufficiently high that the rods will penetrate modern armor steel configurations. However, such rods must have high stiffness (that is, high elastic modulus) to resist bending during launch and flight because slight bending may lead to yaw during flight and a glancing blow off the target. The uranium-titanium alloy described above is a marginal candidate for use in the proposed penetrator rods because its elastic modulus is not high enough. Design analysis shows that *composites* of depleted uranium and of tungsten (whose elastic modulus for bending is three times that of uranium) improve the stiffness of the rod and thus, potentially, its performance. The stiffness of the composite rod is directly related to the geometric placement of the high-modulus material in the rod. It is possible to arrange the composite so that maximum stiffening is achieved with the least change in penetrator density.

Early in the development of the composite penetrator, we realized that the difference between the coefficients of thermal expansion of the two materials was sufficiently large that the tungsten either fractured or buckled slightly, causing it to lose collinearity with the penetrator axis. Both these effects, of course, are detrimental to the properties of the composite as a penetrator. We added various metal powders to the uranium component and found, for some, that the coefficients were matched more closely. In fact, both the thermal-expansion coefficient and the elastic modulus were altered according to the "rule of mixtures" (the value of a property of a mixture is the sum of component values, each weighted by the relative concentration of the component).

We tested tungsten-uranium composite rods in which the uranium was reinforced with metallic particles. There was both an expected slight increase in elastic modulus (25 per cent) and an unexpected but significant increase in yield strength. For example, the *tensile* (stretching) yield strength increased from the 25,000 psi (pounds per square inch) typical of cast unalloyed uranium to 110,000 psi in the cast composite, an increase of more than 400 per cent.

The significant jump in yield strength was an exciting bonus. Penetrators cast from the uranium-titanium alloy are brittle and therefore must be heat treated, but heat treatment is expensive, time consuming, and prone to formation of voids in the uranium. Composite penetrators can simply be cast without heat treatment, producing rods with yield strengths in the same range as for uranium-titanium alloy penetrators that have been heat-treated. The results to date have identified an optimum composition of metallic powders that produces rods with both high strength and high stiffness.

Another alloy. Our research on these composites has concentrated on developing material with the highest strength compatible with a low enough powder content to preserve ease of casting. Optical micrographs of both the original powder and a cast uranium-metallic powder material (Fig. 7) show that part of the powder, after casting, is present in the uranium as a dispersion of coarse particles. However, the particles are smaller and less angular than those found in the starting powder itself, which indicates that part of the metal dissolves in the uranium, forming another alloy. Significantly, regions of fine particles are also observed; apparently, some of the dissolved metal reprecipitates during the cooling process. Our studies indicate that the precipitation is the principal cause of the strengthening of the material.

The addition of metallic powder to uranium has been so effective in minimizing the mismatch of thermal expansion coefficients in the composite that fabrication of full-scale penetrators have yielded crack-free rods that require no further heat treatment before machining (Fig. 8). The simplicity of processing is a significant advantage for manufacture. Further, subscale ballistic tests have shown that uranium-tungsten composite rods can penetrate targets at relatively low velocities, whereas pure uranium rods failed to penetrate the same targets at *any* velocity.

Our work to date on the mixtures of uranium and metallic powder also hints at the possible development of a new high-strength uranium alloy with other highly desirable features not possessed by, say, the heat-treated uranium-titanium alloy. Weldability of the material is quite good, and bend tests show it to have significantly enhanced ductility (the ability to be deformed without fracture).

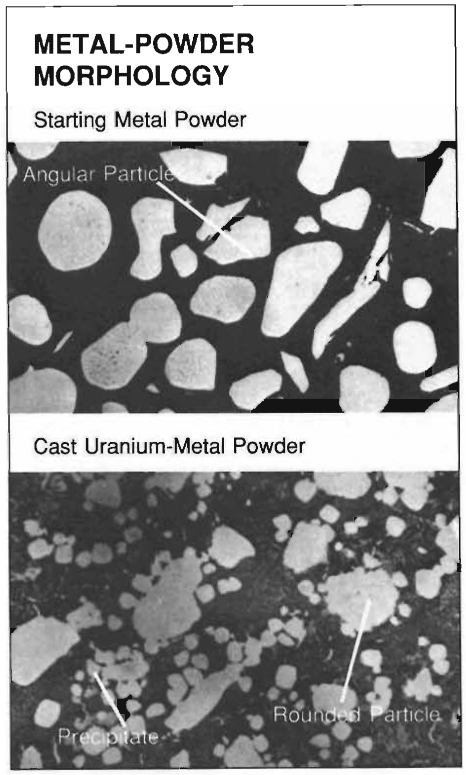


Fig. 7. These optical micrographs show the changes in morphology that occur when metallic powder is mixed with uranium and then cast at about 1350°C. The fact that the occasional sharply angular regions in the original powder have disappeared in the cast material indicates that part of the metal dissolved in the uranium, and the presence of finer particles in the cast material indicates that part of that dissolved metal reprecipitated on cooling.

Among the many aspects of the alloy that are of interest and that need to be studied are the following:

- confirmation of the alloy phase diagram, especially the solid solubility of the metal in uranium;
- determination of the precipitation mechanism;
- variation of the metal grain size with thermomechanical processing;
- effect of size and size distribution of

particles in the powder on mechanical properties;
- dependence of fracture toughness and other mechanical properties on temperature;
- large-strain behavior and work-hardening characteristics;
- resistance to chemical and stress-induced corrosion; and
- relationships between the microstructure and material properties.

Low-pressure plasma spray. Cost is a major consideration in the development of any armor or anti-armor component. Generally, but not always, the cost of the raw material is only a small fraction of the overall cost of a component, and significant savings can be realized by reducing fabrication costs. In general, we have found that simple materials coupled with reliable engineering and assembly lead to cost-effective components. With that approach in mind, we have investigated low-pressure plasma spraying as a possible fabrication technique for such things as composite penetrators.

The plasma-spray process that we have developed uses a DC-arc plasma-spray torch in a chamber filled with inert gas at a low pressure (Fig. 9). A high-velocity stream of high-temperature plasma melts injected powder particles and propels the molten droplets against a substrate. The result is a rapidly solidified deposit of fine-grained material.

Our facility features a single DC-arc plasma-spray torch with *two* powder-feed inlets. The two inlets allow us to deposit two materials simultaneously. Four axes of manipulation are available between the spray torch and the substrate. Plasma spraying should prove to be faster and cheaper than any other means of fabricating composite penetrators.

Chemical-Energy Penetrators

As mentioned earlier, the second class of penetrators is the chemical-energy penetrator. This weapon defeats armor by using the chemical energy of a shaped explosive charge, ignited on impact, to propel a metal liner at the target. Typically, the liner is a conical shell bonded to a machined hollow in the charge opposite the detonator with the base of the cone pointing outward toward the target (Fig. 10). The shape of the charge focuses much of its explosive force onto the metal liner, turning it inside out and stretching it to form a long jet of solid material. (In other versions of the weapon, a compact, high-velocity slug is formed.) In effect, the liner becomes a kinetic-energy penetrator but with typical impact velocities of about 7 kilometers per second compared to 1 or 2 kilometers per second for normal kinetic-energy penetrators. Although a kinetic-energy penetrator travels from gun to target at high velocity, a chemical-energy weapon can work even if the device is simply *placed* against the armor and ignited.

Los Alamos has applied much of its knowledge about materials to the development of liners for the chemical-energy weapon, and liners made from unalloyed uranium represent the most effective such penetrator currently available. The fact that the physical and mechanical properties of materials are important determinants of the performance of a munitions component is nowhere more evident than in the case of those liners. For example, the ability of a liner to form a long, stable jet depends in an extraordinary way on both the physical properties of the material and the process-induced mechanical properties.

To achieve ideal performance, a precisely fabricated shell of depleted uranium bonded into the machined cavity of high explosive must, upon detonation, produce a long, thin, *unbroken* jet of metal traveling at a high velocity. The jet elongates in flight and must have sufficient dynamic ductility to prevent breakup before striking the target. Such ductility depends strongly on the metallurgical history of the liner.

When we recognized that jet breakup was highly dependent on the material's process history as well as on its physical properties, we undertook a program, sponsored primarily by the Air Force Armaments Laboratory at Eglin Air Force Base, to gain a better understanding of how metallurgy affects jet formation. To achieve this understanding, we studied uranium and other metals with different crystal structures. A number of metallurgical factors emerged

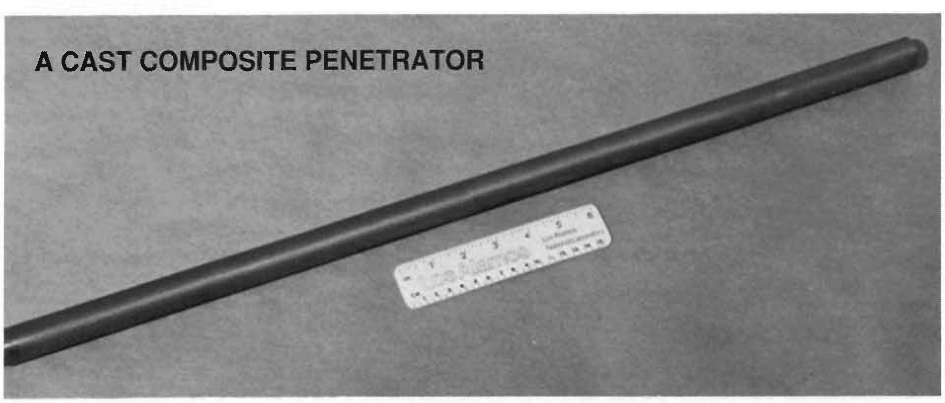


Fig. 8. Crack-free composite penetrator rods of tungsten and uranium have been successfully formed by more closely matching the thermal coefficients of the two materials. The match was achieved by adding metal powder to the uranium.

that have an important bearing on liner performance.

The key to these desired mechanical properties is the production of an appropriate crystalline microstructure in the formed liner blanks. To achieve the correct microstructure, we first select a material whose properties are highly sensitive to mechanical deformations and then subject that material to a series of carefully manipulated deformations and heat treatments. To learn more about formation of the preferred microstructure, we monitor our materials carefully during the various stages of deformation. Mechanical properties of the fabricated sheet are measured in three orthogonal directions in the material, crystallographic orientation of the grains are determined using x-ray diffraction, and the development of the microstructure is followed using various metallographic techniques.

In addition to our success with depleted-uranium jets, we have shown that liners with reproducible characteristics can be formed from other metals. In fact, some of our experimental metal liners produce particularly long ductile jets with very late breakup times. The same careful attention to processing history and development of the appropriate crystalline microstructures are critically important for these metals also.

PLASMA-SPRAY DEVICE

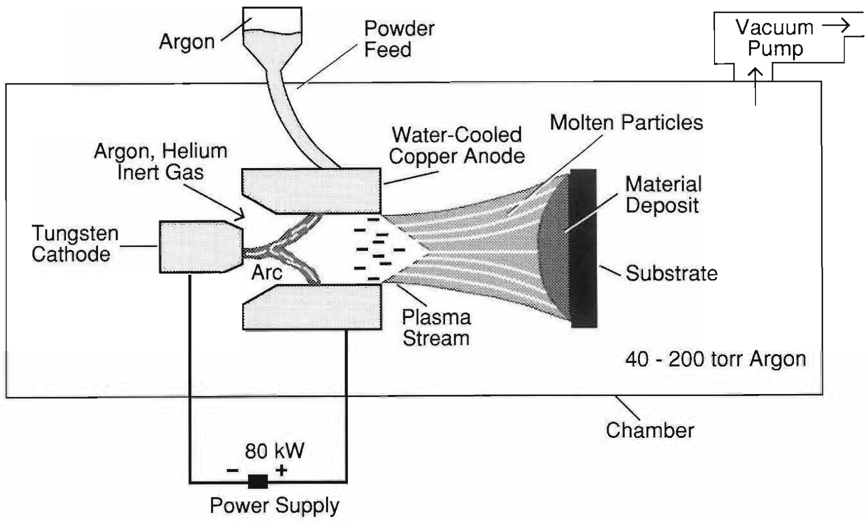


Fig. 9. This schematic depicts the major components of a low-pressure plasma-spray device being used at Los Alamos to explore the low-cost fabrication of such objects as composite penetrators. An 80-kilowatt arc is generated in a mixture of argon and helium gases by applying a DC voltage across the gap between a tungsten cathode and a cylindrical water-cooled copper anode. The arc creates a high-temperature, high-velocity plasma stream moving to the right. Powder fed into this region collides with the stream, melts, and is propelled as molten droplets onto a substrate, where it quickly solidifies, producing a fine-grained deposit. A second powder feed (not shown) allows one to run the feeds simultaneously, producing a layer of mixed material. The whole device operates under a reduced pressure of argon, and the powder feeds operate by being pressurized with argon.

Ceramic Armor

The opposite side of the coin from penetrators, of course, is armor. Here also knowledge of material properties is of critical importance to the design of armor packages that will defeat a wide range of penetrators.

Any material used to defeat a high-velocity projectile must deal with the kinetic energy and momentum of that projectile with some combination of three mechanisms: 1) absorption of the energy as heat and deformation in the *target* material, 2) rebound of the projectile, which is how steel armor deals with a steel projectile, and 3) gross deformation of the *projectile*. The last mechanism is the most efficient way for armor to defeat projectiles because most of the kinetic energy is absorbed in the destruction of the projectile itself and, with little rebound of the projectile, momentum transfer to the armor is minimized. Unfortunately, conventional steel armor is not capable of defeating high-hardness projectiles, such as armor-piercing bullet cores and tungsten rods, in this way.

As a result, a variety of armors have been developed, including multilayered composites and *reactive* armor. (Reactive armor has a layer of explosive material that ignites on impact, blowing a facing plate outward to deflect or destroy the projectile.) However, one of the key problems facing armor designers is weight—a well-armored tank may, in the end, be too heavy to move. As a result, there is a need for armor systems that are light but difficult to penetrate.

One approach to weight reduction has been the use of ceramics, which offer exceptional protection for very light weight. Some of the relevant ceramic materials are aluminum oxide (Al_2O_3), silicon carbide (SiC), boron carbide (B_4C), and titanium diboride (TiB_2), all of which have high hardness with an associated abrasiveness, high compressive and tensile strengths, and good elastic properties to high stress values.

Microwave processing. High cost is currently one of the disadvantages of ceramic armor, and, as pointed out earlier, cost is a major consideration in the development of any weapons component. A significant portion of the cost of ceramic armor lies in the fabrication of monolithic ceramic plates with the required high density. Here, again, we have attempted to reduce fabrication costs—in this case, by using microwave radiation to process the ceramic.

The ceramics of interest for armor materials are currently processed using hot pressing (in which graphite dies apply high uniaxial pressure while the material is slowly heated) or using hot isostatic pressing (in which an inert gas applies high isotropic pressure to the material in a heated chamber). These techniques generate the high densities needed for ceramic armor but are expensive and slow.

Microwave processing, using the commonly employed frequency of commercial microwave ovens (2.45 gigahertz), achieves the required high densities by starting with cold-pressed ceramic powder and rapidly *sintering* it (heating without melting until the material forms a dense homogeneous mass). Microwave processing is much faster, and therefore less energy-consumptive, than conventional hot pressing, and the equipment needed is considerably less expensive.

Microwave processing also produces a superior material because the heating occurs rapidly throughout the entire volume of material. Traditional processing methods, which depend upon conduction from surface to interior, promote growth of large crystal grains in the material because of prolonged heating, much as overbaking creates a rough, crumbly texture in bread. Microwave sintering couples energy rapidly throughout the material and thereby favors densification of the material over grain growth. The end result is a ceramic with a finer grain size, fewer voids, and fewer stress cracks and thus better mechanical properties, such as greater strength and higher resistance to ballistic penetration.

Microwave processing also offers advantages in the final fabrication steps. Hot pressing can produce only simple shapes that must then be machined into the desired forms. Depending on the density and eventual application of the ceramic, the machining may require many extra hours and the use of expensive diamond-tipped cutting tools. Microwave processing can be applied to shapes close to those required for the ultimate use.

Although microwave sintering of ceramics is not new, we took the process a step further by combining precise positioning in the microwave oven with insulation techniques that reflect and concentrate the radiated energy on the sample, much as snow or sand reflect sunlight back to the skin. The resulting greater thermal efficiency of the process improved the sinterability of difficult materials such as aluminum oxide, boron carbide, and titanium diboride. We have, for example, been able to sinter boron carbide to 95 per cent theoretical density (Fig. 11). The time required to heat the material from room temperature to over 2000 degrees centigrade is under 12 minutes, whereas conventional hot pressing takes several hours. The capital costs for the Los Alamos microwave facility were less than $35,000, whereas a 3-inch-diameter hot press, the equipment needed to densify a boron carbide sample of the same size, costs between $120,000 and $200,000. Further, energy costs were cut about 18 per cent.

We are also working on a new com-

THE CHEMICAL-ENERGY PENETRATOR

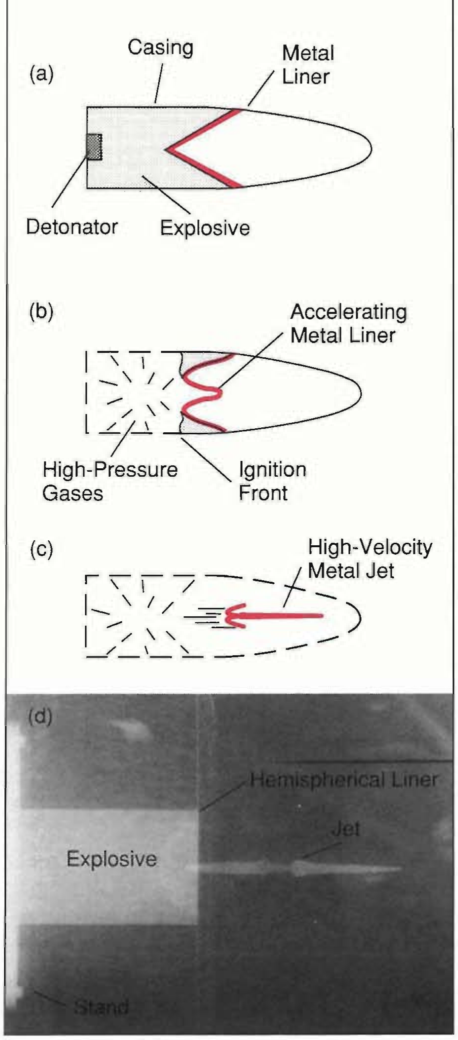


Fig. 10. (a) The conical shape of a typical chemical-energy penetrator is designed to focus the explosive energy of the charge onto a metal sheet (red) that lines the conical hollow. (b) Because the explosive force in the charge reaches the center of the liner first, this region is accelerated before the outer regions. (c) As a result, the liner turns inside out, stretching into a long jet of material. If the metal liner has the proper materials properties, it will form an unbroken jet and will impact the target at a velocity much higher than that of a typical kinetic-energy penetrator. (d) This doubly exposed radiograph of a chemical-energy penetrator shows the shaped charge on the left with, in this case, a hemispherical liner. The image to the right is the solid jet formed when the charge was fired.

posite .material for armor applications—aluminum oxide reinforced with platlets of silicon carbide. The platlets, being single crystals, have exceptional tensile strength and can be used to increase the fracture toughness of ceramics, metals, and perhaps even polymerics. Less than 10 minutes of microwave processing are required to produce the new composite at 94 per cent of theoretical density, and we expect that material to have very good resistance to ballistic penetration.

Fig. 11. A sample of boron carbide is rapidly sintered in a microwave oven to produce a fine-grained ceramic with a density that is close to the theoretical maximum.

Ceramic-Filled Polymer Armor

Ceramic armor for, say, lightweight fighting vehicles and armored personnel carriers currently consists of an outside layer of high-density ceramic tile bonded to a backing plate. Conventional wisdom about such armor had suggested that the ceramic should have high impact strength and hardness so it can help break up a sharp, hard projectile. That requirement implies the ceramic should possess high elastic impedance combined with high hardness and high compressive strength.

Another property that had been felt to be important for ceramic armor is high tensile strength. The impact load transmitted through the ceramic produces compressive stress on the backing plate and a corresponding tensile stress on the rear surface of the ceramic tile. The result is plastic yield in the ceramic and the development of a fracture conoid. A ceramic with high tensile strength would resist such fracture.

However, research by Mark Wilkins at Lawrence Livermore National Laboratory indicates that the most important mechanism for defeat of a projectile by ceramic armor is abrasion. The fracture conoid in the ceramic spreads from the point of impact and generates sharp fragments that are instrumental in helping to abrade or erode the projectile.

We recently performed a series of ballistic tests on a new type of armor, *ceramic-filled polymer* armor, and the results were exceptional. Our new material typically consists of a ceramic aggregate (about 85 per cent ceramic by weight) mixed with a binding polymer or other carrier. Such a material possesses essentially none of the mechanical properties deemed important for ceramic armor. In fact, the *primary* mechanism for defeat—erosion of the penetrator—depends upon the tendency of the new material to fragment fully.

Design and fabrication. The ceramic-filled polymer serves to illustrate the importance of the entire design of an armor package. One of the important properties of this material may be its *dilatancy*, that is, its tendency to readily expand into any free volume when fractured. But whether dilatancy works to advantage in the erosion process may depend critically on how the material is confined.

The effect of packaging on dilatancy can easily be demonstrated by using rice to represent the ceramic-filled armor and a pencil to represent the projectile. If a pencil is pressed down into a beaker filled with rice, resistance will be slight.

TESTING CERAMIC-FILLED POLYMER

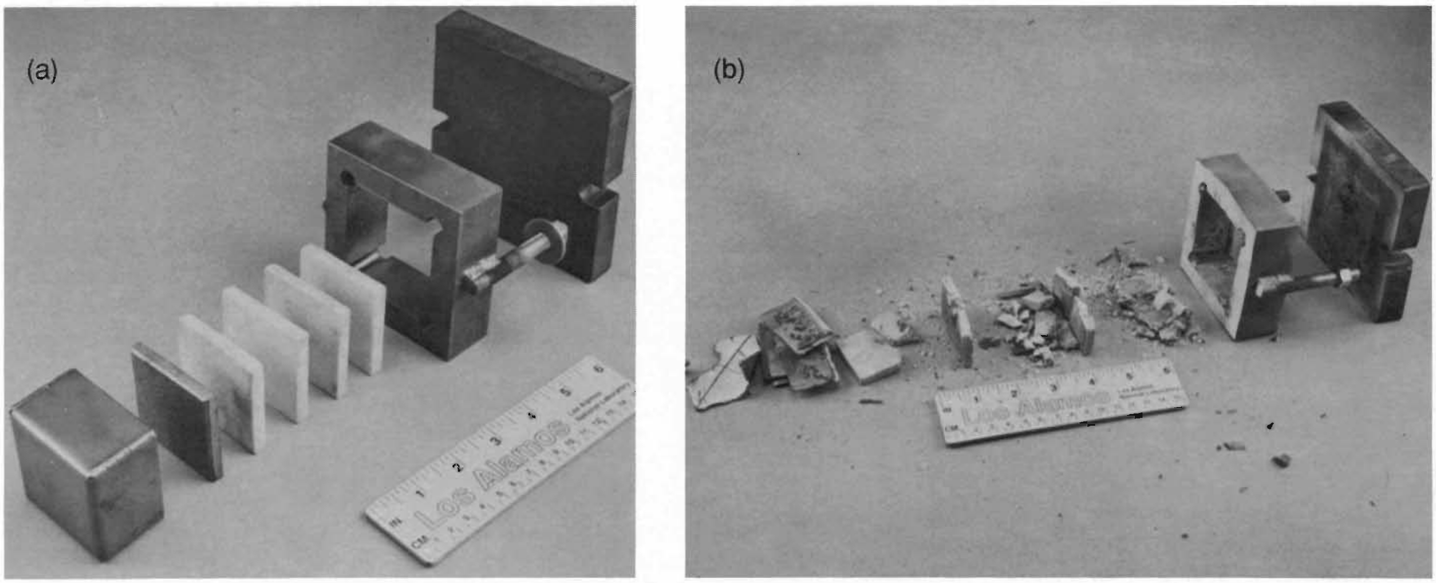


Fig. 12. The before and after of a test of the stopping power of ceramic-filled polymer. (a) The various pieces of the test configuration in the order in which they are put together, including polymer plates (white), the target holder that constrains the polymer (the metal pieces on the left and at the center), and the armor plate being protected by the polymer (the metal piece on the far right). (b) The same pieces after the plates have stopped a projectile without significant damage to the armor plate.

But if the rice is confined to a flask with a narrow neck, resistance to the pencil will be much larger because the rice is unable to move out of the way of the pencil. Free volume is available for expansion in the first case but not in the second.

Although a complete explanation of the excellent results of ceramic-filled polymer armor has not yet been obtained, it appears that dilatancy is involved. A chunk of unconstrained polymer simply blows away on impact with little or no effect on the projectile. A properly designed armor package, however, totally constrains the ceramic-filled polymer (Figs. 12 and 13), say with a backplate and surrounding layers of a high-performance polymeric fiber like Kevlar©. On impact the only free volume is the hole generated by the projectile itself as the armor is hit and fractures. The resulting expansion of the ceramic-filled composite generates a very large number of highly erosive ceramic particles that may be forced out between the sides of the hole and the penetrator, eroding the projectile.

These properties, of course, are quite different from those usually thought of as ideal for ceramic armor. In fact, the ultimate tensile strength of ceramic-filled polymer armor is limited by the strength of the polymer binder, which typically is much lower than that of monolithic ceramic. Another property of the aggregate limits compressive strength—the polymer bonding agent becomes fluid at low applied

CERAMIC-FILLED POLYMER ARMOR

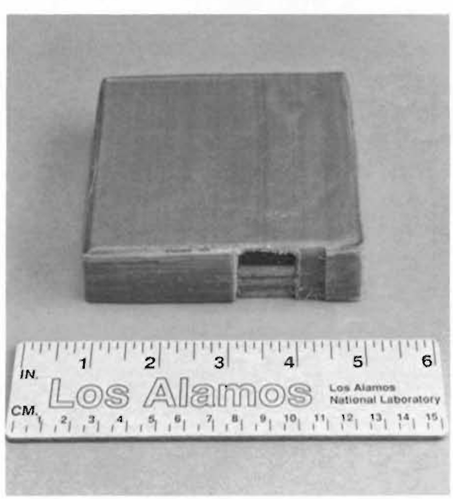


Fig. 13. This sample of polymeric armor has been cut open to reveal the various layers of ceramic-filled polymeric plates confined beneath Kevlar©. The ceramic used in the front plate (black) is boron carbide; the ceramic used in the other plates (white) is aluminum oxide.

shear stress. This phenomenon, called *thixotropy*, can be capitalized on during manufacture or repair of the armor because the aggregate-filled polymer will flow under a constant applied forming pressure, allowing the armor to be cast or molded at low temperatures.

Lightweight armor systems are currently made of high-density ceramic tiles—a very expensive process because the ceramic requires high-temperature fabrication and extensive finish grinding. The polymeric armor requires no high-temperature fabrication or expensive finishing steps and can be easily formed to any required shape, including very large and thick or very geometrically complicated shapes. Additionally, monolithic ceramic suffers from a limited ability to withstand multiple hits because of its propensity to break up, whereas polymeric armor, although highly fractured by the impact, mostly remains in place.

Ballistic tests on an armor package containing ceramic-filled polymer tiles have shown exceptional results. On an equal-volume basis the polymer-bonded material is almost equal to a high-density, high-purity aluminum oxide ceramic tile. On an equal-*mass* basis the ceramic-filled polymer is better!

Ceramic-filled polymer armor can offer four important advantages over conventional ceramic armor:

- a reduction in weight of about 10 per cent since more than 10 per cent of the ceramic is replaced with low-density polymer bonding agent;
- a reduction in manufacturing cost of greater than 50 per cent due to low-temperature fabrication and elimination of expensive grinding steps;
- greater ease of in-field repair since either prefabricated, lightweight tiles or the ceramic and polymer constituents can be stored on board the vehicle; and
- greater ease of accommodating design improvements, such as incorporation of very hard boron carbide plates in the modular package to increase the capability of the armor to break up penetrators.

We are currently exploring in greater detail both the abrasion-erosion mechanism of defeat and the exact contribution of packaging constraints on armor effectiveness. Those effects must be studied systematically if we are to exploit ceramic-filled polymers for fabricating inexpensive, reliable, lightweight armor for mobile fighting vehicles (see "ATAC and the Armor/Anti-armor Program").

A variety of other research on armor and anti-armor materials takes place at Los Alamos. Those studies range from investigation of other alloys for penetrators to the use of chemical vapor deposition to infiltrate "open mesh" composite materials. The latter has a particularly high potential for improving the properties of ordnance components such as gun barrels and sabots.

We believe that materials technology is the enabling—or limiting—technology for virtually all conventional weapons systems. Materials science and technology has progressed to the point that "tailored" properties of materials are a reality. The effects of microstructure on liner performance for chemical-energy weapons, the adjustment of the coefficient of thermal expansion and the accompanying improvements in mechanical properties of the tungsten-uranium composite penetrators, and the exceptional protection offered by ceramic-filled polymer armor are examples of rather straightforward applications of developments in materials. These developments, though seemingly simple, are grounded in a thorough understanding of materials science and technology. We believe the surface has barely been scratched and that the future in conventional munitions belongs to innovators and designers of new materials. ■

Further Reading

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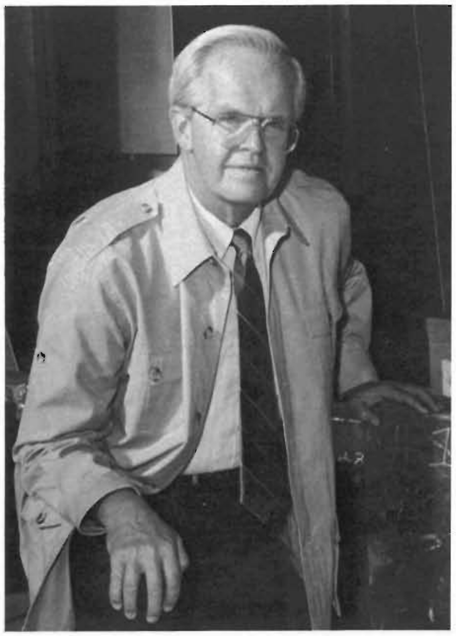


Donald J. Sandstrom is Deputy Division Leader of the Materials Science and Technology Division at the Los Alamos National Laboratory. He is responsible for working closely with the division leader in managing all aspects of the division's operations including scientific and technical management, people management, strategic and tactical planning, and organizational development. He received his B.S. in metallurgical engineering from the University of Illinois in 1958 and his M.S. in the engineering science of materials from the University of New Mexico in 1968. Before joining the staff at Los Alamos in 1961, he was a metallurgical engineer for ACF Industries from 1958 to 1961. At Los Alamos he helped pioneer much of the materials work in armor and anti-armor, including the development of depleted uranium alloys for penetrators and the development of ceramic-filled polymer armor.

Some of the people responsible for the work described in this article include (from left to right) Anna Zurek (high-strain properties of materials), Joel Katz (microwave processing), Phil Armstrong (materials properties and characterization), Noel Calkins (development of composite armor), Pete Shalek (ceramics processing), Paul Dunn (development of composite kinetic-energy penetrators), Paul Stanek (development of low-pressure plasma spraying), Don Sandstrom, Billy Hogan (Program Manager for the kinetic-energy penetrators), and Robert Reiswig (chemical-energy penetrators and materials characterization).

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 microstructures. 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'être 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.

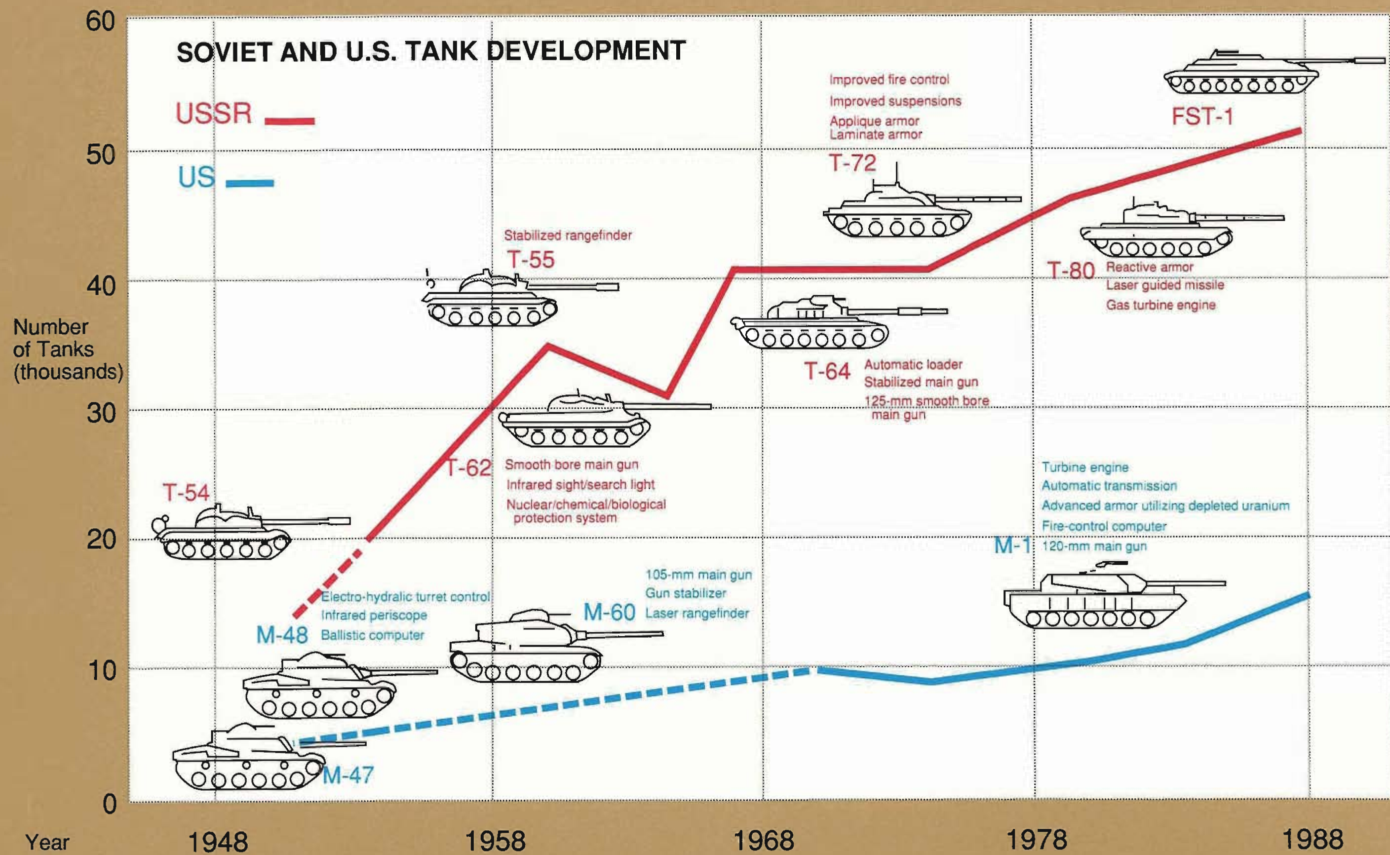
"The Task Force called this decline of information during full-scale engineering *the Bathtub of Ignorance*. Historically, it has taken us at least five years to catch up and frequently as long as fifteen years to apply the same technology in our fielded systems.

"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



* 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-1
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/metric 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 emphasizes 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 T-80) 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

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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.

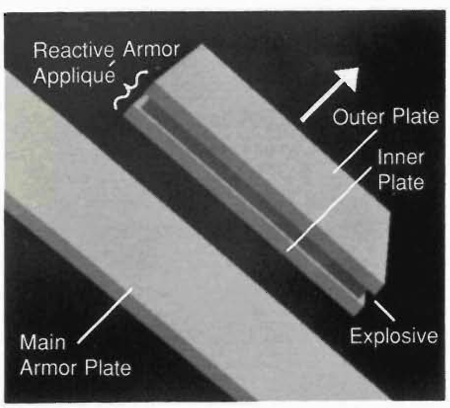
gun-fired kinetic-energy penetrators by a factor of at least two to one. Also, the destructiveness of the chemical-energy penetrator is not dependent on the energy of the delivery system because the penetrator is formed and driven by explosives in the warhead. No barrel is required to direct the penetrator, 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 appliqués 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



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.

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.

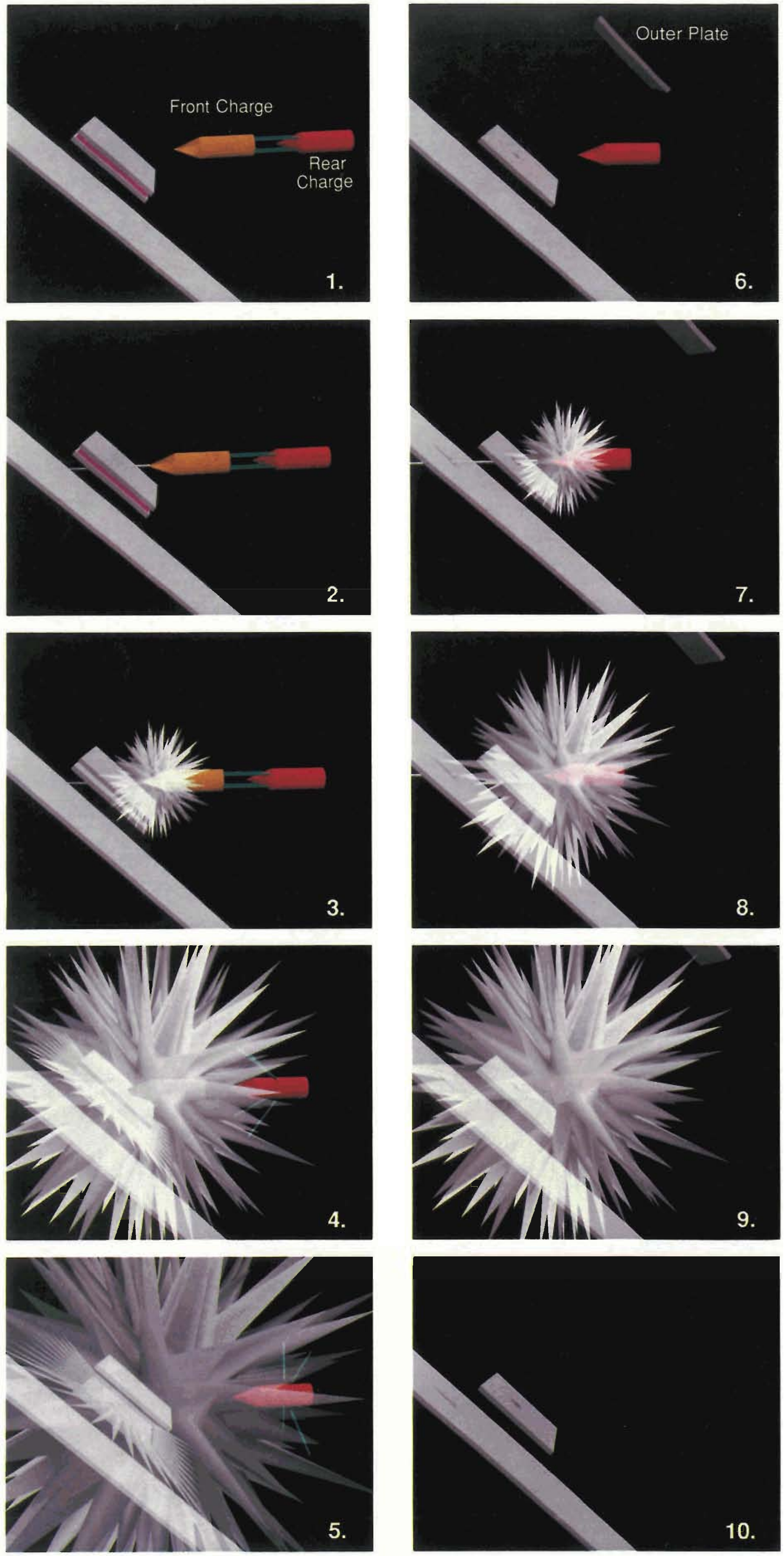
We can, however, talk about one promising concept—tandem chemical-energy warheads (Fig. 3). In these weapons a small charge at the front of the warhead fires to activate the tank's reactive armor. A time delay allows the reactive-armor plates to move out of the way, then a large shaped charge further 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 fins 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.

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.

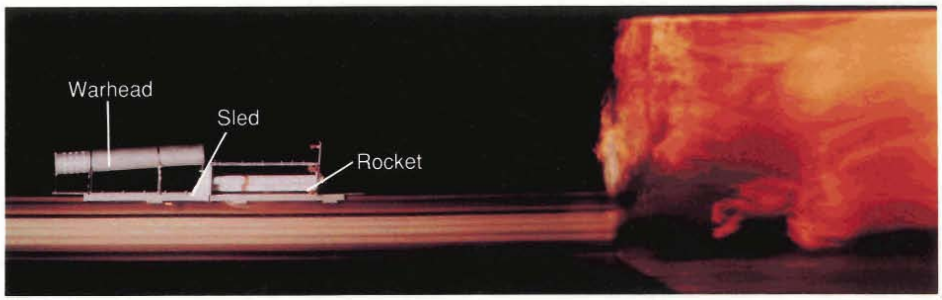
We are also building a new intense flash x-ray machine next to the sled track. This machine should allow armor and anti-armor developers to "see" the penetration process through eight inches of steel (Fig. 5). The source in this system will operate at 8 to 10 mega-electron-volts (MeV) and generate an 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.

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 30-nanosecond shutter times, a laser velocimeter and a microwave

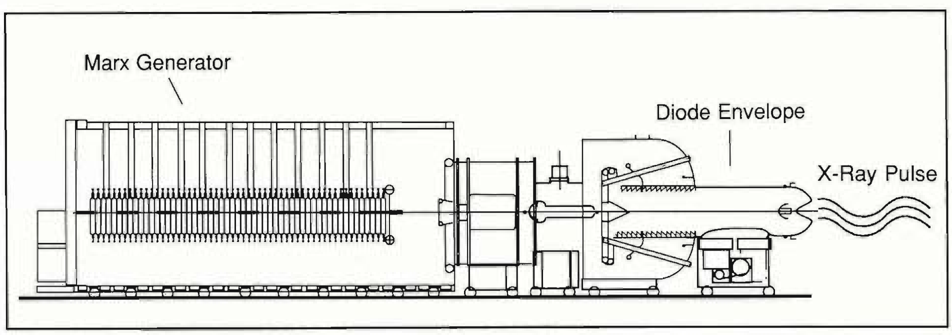
ROCKET SLED

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.



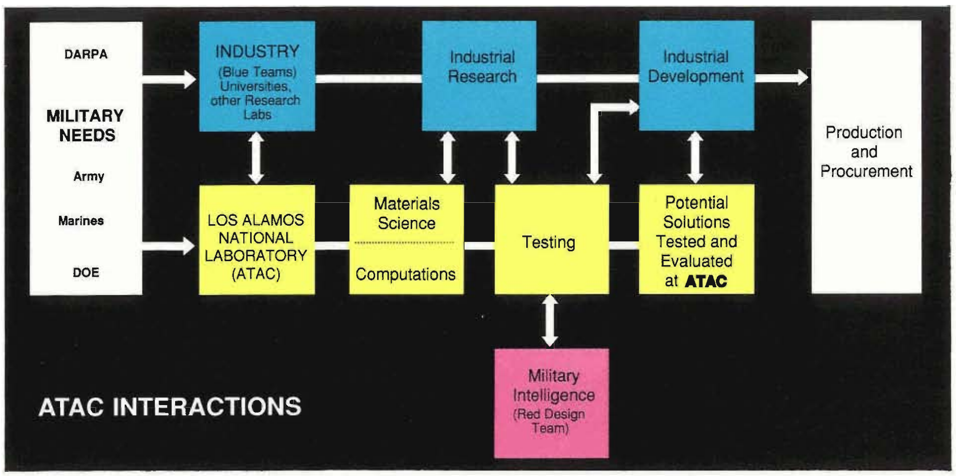
FLASH X-RAY MACHINE

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.



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. ■

Richard Mah is the director of ATAC and a former group leader in the Materials Science Division at Los Alamos. Prior to coming to the Laboratory, he worked as a senior research engineer at Dow Chemical and C. F. Braun & Co. He holds degrees in theoretical and applied mechanics and metallurgical engineering from the University of Illinois and has published over twenty papers on materials science topics.

Phyllis Martell is the technical writer and public relations manager for ATAC at Los Alamos and publishes a newsletter, *The BULLET*, on Armor/Anti-Armor Program activities. Before joining the Laboratory, she was the public information officer for the Los Alamos School District. She holds a degree in French and English from the University of Wisconsin.

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.

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

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

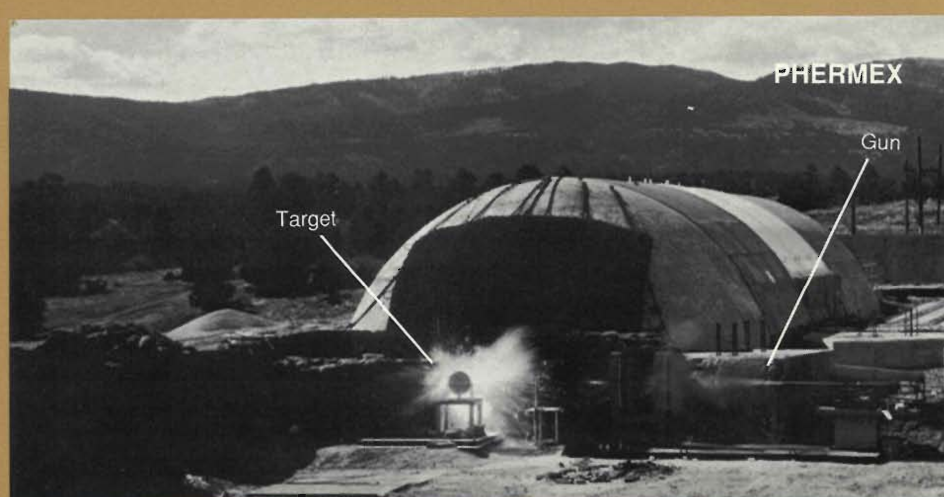


Fig. 2. A flash x-ray machine (in the building behind the target) is currently being used to produce high-resolution radiographs (see Fig. 4) of the ballistic interaction of ceramic targets with long-rod penetrators (fired from the gun at the right).

understand what those differences are.

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. Modern 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.

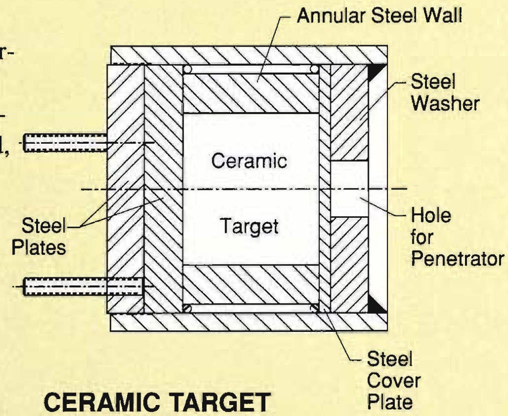


Fig. 3. The targets used to study the response of ceramic to impact by a penetrator rod were designed to keep the ceramic confined during the event. The penetrator rod enters the front of the target through the hole in a steel washer and then strikes a hardened steel cover plate. At a predetermined time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

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.

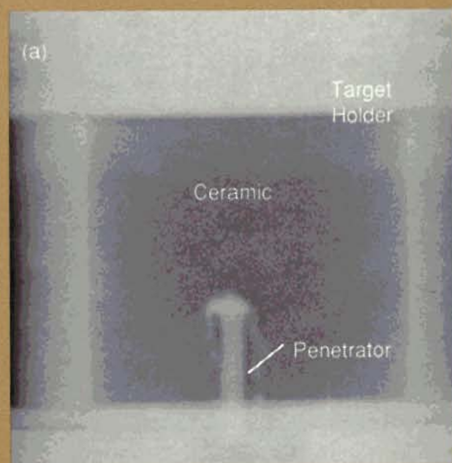
We use targets that are thick enough to stop the penetrators in the ceramic and make a radiograph of the target after each shot to show the final penetration depth and the length of any remaining rod or jet material. A sequence of four to six nominally identical shots produces a time-resolved penetration 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 general feature for the defeat of jets fired from chemical-energy weapons. In this mechanism the ceramic rubble refills the impact hole, constantly forcing the jet to penetrate new material, and, as the

CERAMIC PENETRATION



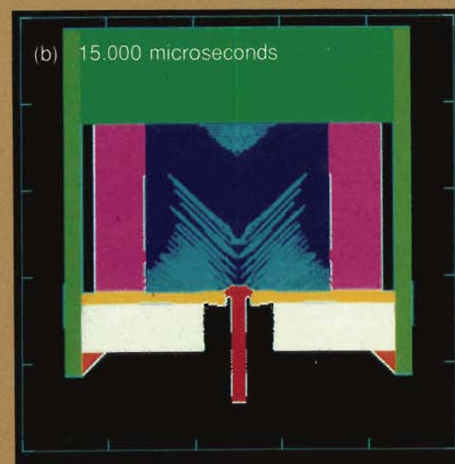


Fig. 4. (a) A PHERMEX radiograph of a tungsten-alloy penetrator colliding with the ceramic target of Fig. 3. (b) The same event at the same moment in time as simulated with the HULL hydrocode. (See "Modeling Armor Penetration" for a discussion of the hydrocodes.) The light blue areas in the computer 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 based 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.

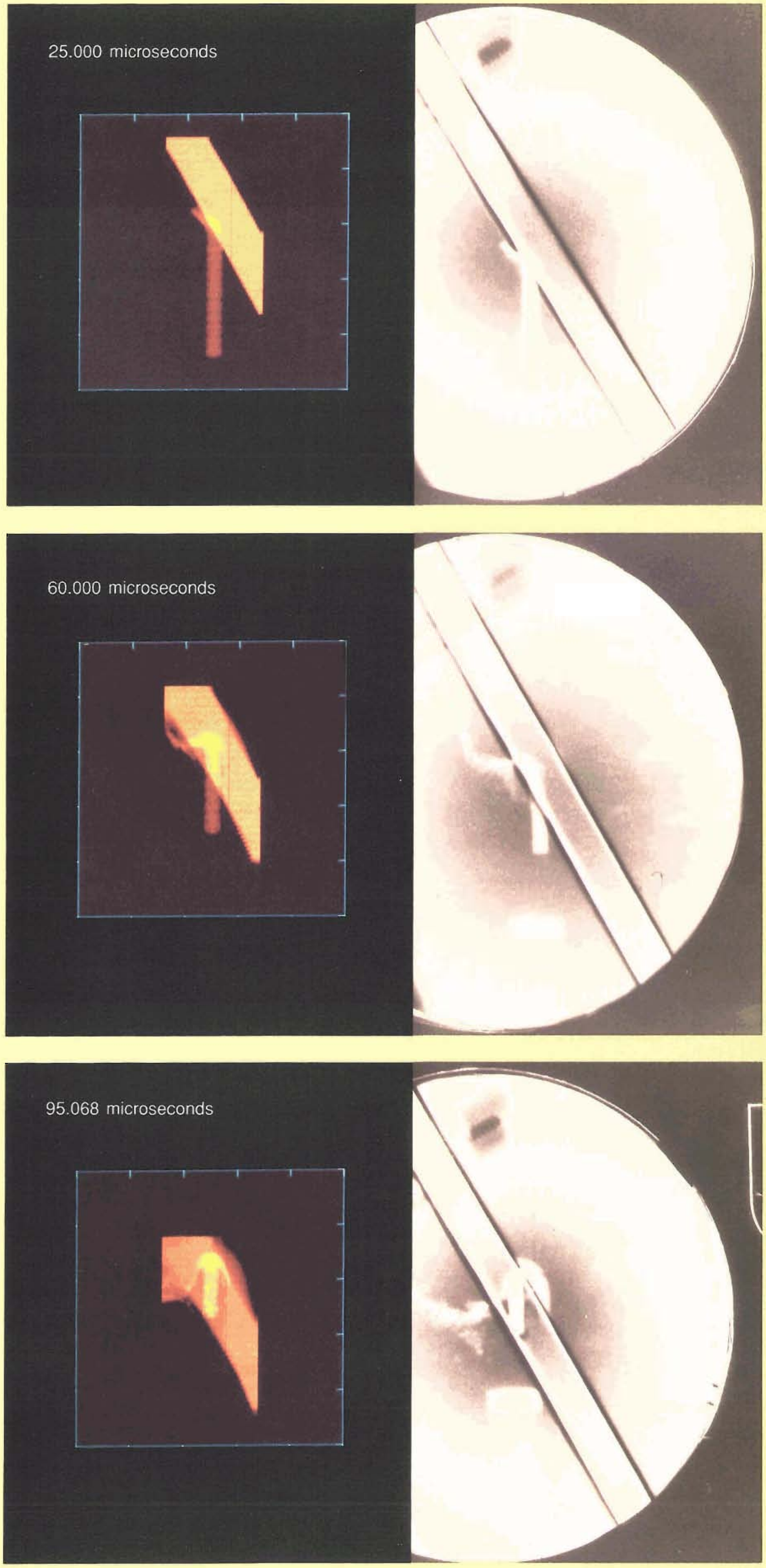
In our work at Los Alamos, we first explored an existing three-dimensional Eulerian code, HULL. We wanted to test its ability to accurately predict penetration of *spaced* armor, which has multiple layers of armor separated by gaps and set at oblique angles to the penetrator's line of flight. The intent 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-burn 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 applications 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. ■