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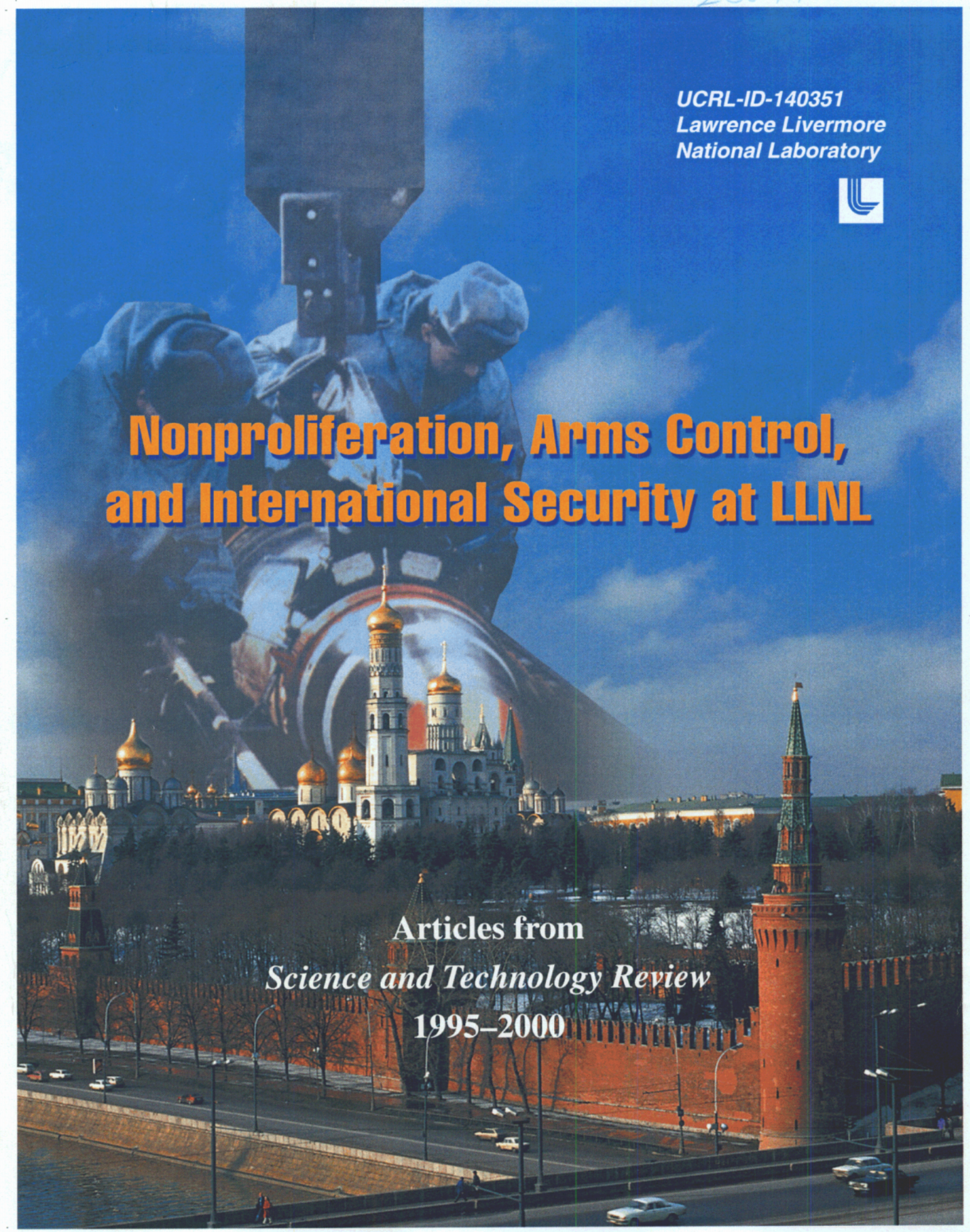

Nonproliferation, Arms Control, and International Security at LLNL

Articles from

Science and Technology Review

1995–2000

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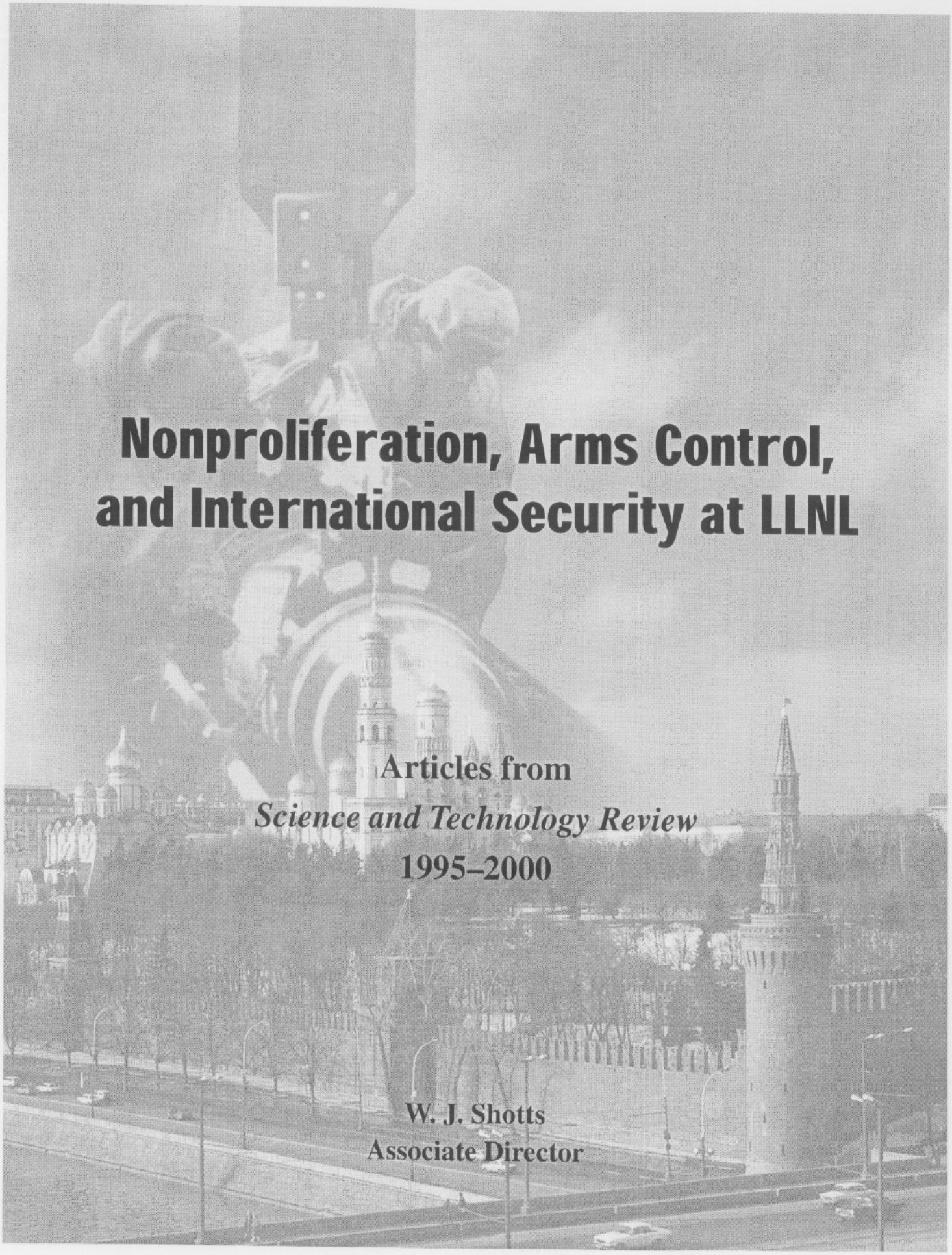

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W. J. Shotts
Associate Director

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Preface

NAI's Mission

LLNL's Nonproliferation, Arms Control, and International Security (NAI) Directorate enhances national and international security by providing technology, analysis, and expertise for the U.S. government to use in preventing the spread or use of weapons of mass destruction.

The Threat

Ten years ago, the consuming national security threat to the U.S. was the nuclear arsenal of the Soviet Union. The energies, talent, and resources of the national security laboratories were dedicated to checkmating the Soviet threat. That world no longer exists. The Soviet Union has collapsed, and the direct Russian nuclear threat is greatly diminished.

Today, the most serious threat to national security arises from the proliferation of nuclear, chemical, and biological weapons (collectively known as weapons of mass destruction or WMD). Political and economic instabilities plaguing Russia have given rise to new concerns, particularly as related to Russia's role as a supplier, unintentional or otherwise, of weapons-usable nuclear materials and weapons know-how. India's and Pakistan's emergence from the "nuclear closet" has shaken the foundations of the global nonproliferation regime. Regional conflicts continue to erupt, and 20-some countries (some of them hostile to the U.S.) are suspected of or known to be developing nuclear, chemical, and/or biological weapons. The nerve-gas attacks on the Tokyo subways raised the specter of terrorist use of weapons of mass destruction.

The proliferation threat is extremely complex. There are myriad routes to weapons of mass destruction— many different starting materials, material sources, production processes, and deployed weapons. There are many possible proliferators—threshold countries, rogue states, state-sponsored terrorist groups, domestic terrorists, and even international crime organizations. Motives for acquiring and using weapons of mass destruction are similarly wide ranging—from a desire to change the regional military balance, deny access to a strategic area, or alter international policy to extortion, revenge, or hate.

Securing Peace in the 21st Century

U.S. national security rests on the twin pillars of threat reduction—by preventing the spread or use of weapons of mass destruction—and deterrence—through military strength, treaties, and diplomacy. Both national security thrusts involve a complex combination of policy and technology. Indeed, the strength of arms reduction, nonproliferation, and test ban treaties is based, in large part, on technical capabilities for detecting and evaluating evasion attempts and for monitoring and verifying compliance.

We apply expertise in nuclear weapons, developed through the Laboratory's historical weapons program and its continuing stockpile responsibilities, to the challenge of nuclear nonproliferation. Because the proliferation threat is not limited to nuclear weapons, we build on LLNL's large investment in the chemical and biological sciences to develop technologies and expertise to stem the spread of chemical and biological weapons.

At Livermore, we have implemented an integrated program to address the WMD proliferation problem from end to end—prevention, detection and reversal, and response, while avoiding surprise at all stages. In addition, our Center for Global Security Research provides a bridge between the technology and policy communities, bringing them together to explore ways in which technology can enhance national and international security.

Preventing Proliferation

The best way to stop weapons proliferation is at the source. Because the materials required for nuclear weapons do not occur naturally and are difficult to produce, the most effective way to prevent the spread of nuclear weapons is to protect and control nuclear materials. However, we cannot prevent the proliferation of chemical and biological

weapons by controlling materials because the materials for these weapons are ubiquitous and have many legitimate uses. For all types of weapons, arms control agreements—and verified compliance with the agreements—are an essential element of proliferation prevention.

We have provided technical and analytical support to U.S. arms control efforts for more than 40 years. Over the years, we have contributed to the SALT treaties, the START agreements, the Limited, Threshold, and Comprehensive test ban treaties, and the Chemical and Biological weapons conventions. We assess the impact of proposed treaty provisions in terms of U.S. ability to monitor other countries and to protect sensitive information during inspections of U.S. facilities. We also develop monitoring technologies and data analysis methods and participate in field trials to prepare for inspections in the U.S. and abroad.

The breakup of the Soviet Union raised serious concerns about the security of Soviet-legacy nuclear materials. We are working with Russia and the other former Soviet republics to upgrade the protection, control, and accounting of weapons-usable nuclear materials stored or processed at dozens of research and manufacturing facilities. We are also working with the Russian nuclear navy and the Murmansk icebreaker fleet to enhance the protection of fresh and spent fuel for their nuclear-powered vessels.

Large quantities of surplus nuclear materials are resulting from the dismantlement of thousands of nuclear weapons, both in the U.S. and Russia. We are collaborating with the Russians to develop suitable technologies for the permanent disposition of excess nuclear materials as well as mutually acceptable detection methods for increased transparency during the dismantlement process.

We are also working with our counterparts in Russia on cooperative projects to adapt their weapons-related technologies and facilities to civilian and commercial applications. These activities address concerns about a potential "brain drain" of former Soviet weapons workers to proliferant countries.

Detecting and Reversing Proliferation

In order to reverse the proliferation of weapons of mass destruction, we must first detect and identify proliferation-related activities. Weapons development, testing, and production each have unique indicators that, if measured, can provide clues as to the intent and status of a country's weapons program. Because the clues are fragmentary and often ambiguous, we must tap many sources of information— satellite imagery, industrial activity, import records, materiel and personnel movement, chemical analyses of water, soil, and air—to assemble a reliable overall picture.

If weapons-related activities are detected, the next step is to evaluate options for reversing proliferation. We provide U.S. policy makers and military planners with the tools and information needed to evaluate the implications of various actions. We have developed a powerful and comprehensive system for analyzing weapons proliferation activities of foreign countries, identifying critical facilities, and evaluating the consequences of possible interdiction options.

We are developing technologies to remotely monitor weapons proliferation activities and to protect critical U.S. facilities and troops from attack. For example, we are developing various remote sensing systems that can identify trace chemicals released into the atmosphere from industrial facilities. This is an extremely difficult challenge, requiring significant advances in remote detection instrumentation and data analysis techniques. We are also developing new types of sensors, incorporating cutting-edge advances in nanoengineering and communications, as well as various techniques for integrating networks of sensors.

Responding to Threats or Use of WMD

Despite all attempts to prevent the spread of weapons of mass destruction and to reverse proliferant weapons programs, we must also be prepared to respond to the threatened or actual use of a nuclear, chemical, or biological weapon. We provide expert personnel and technical capabilities for the nation's nuclear incident response groups, including the Radiological Assistance Program, the Accident Response Group, and the Joint Technical

Operations Team. Our Nuclear Threat Assessment Program provides technical, operational, and behavioral evaluations of nuclear extortion threats and assessments of cases of illicit trafficking of alleged nuclear materials.

We are a major participant in the Department of Energy's Chemical and Biological Weapons Nonproliferation Program. We lead the program's thrusts in biofoundations and modeling and simulation. We have also made breakthroughs in field-portable DNA-detection instruments, including a miniature flow cytometer suitable for a field laboratory, a ten-chamber advanced nucleic acid analysis (ANAA) that functions autonomously from sample preparation through detection and reporting of results, and a battery-powered, four-chamber, handheld ANAA suitable for first responders that can routinely perform DNA analysis and identification in less than ten minutes.

Our Forensic Science Laboratory develops new technologies for ultratrace chemical and isotopic analyses of nuclear, inorganic, and organic materials (chemical warfare agents, drugs, etc.) and biological materials (toxins, DNA, etc.). We also design and construction of new field-portable analytical instrumentation and sample collection methods for use by the law enforcement and intelligence communities.

Avoiding Surprise about Proliferation

Underlying proliferation prevention, detection and reversal, and response is the need to avoid surprise regarding the weapons programs of foreign countries. We conduct analyses and research related to the development and deployment of weapons of mass destruction by countries, states, and groups hostile to the U.S. Our assessments provide important input to policy makers and diplomats as they develop strategies for U.S. responses to events affecting national and international security.

We evaluate nuclear proliferation risks in key areas of the world. Of particular concern are the threshold states (countries developing or producing nuclear weapons for near-term deployment), states with difficult or hostile relations with the U.S., and those located in politically unstable regions of the world. We also analyze the status of the nuclear weapons and weapon materials in Russia and China and the nuclear proliferation threat they pose. Russia's economic and political instabilities put severe stress on controls for safeguarding nuclear material and weapons inventories. China is of concern because of its uneven history related to arms control and nonproliferation and its often-strained relations with the U.S.

We conduct assessments of chemical and biological weapons programs as well. Nuclear, chemical, and biological weapons programs are interrelated in some countries of concern, whereas other countries are pursuing chemical or biological weapons in lieu of more costly and more complex nuclear weapons.

In addition, we are addressing the national security implications of the U.S.'s rapidly growing reliance on critical networked infrastructures and the need to ensure the integrity of information as it is transmitted through national and international telecommunications links serving government and industry. LLNL has become a leader in information assurance technology and has formed partnerships with the agencies chartered to deal with such issues for the U.S. government.

The Policy–Technology Interface

Our Center for Global Security Research brings scientists and technologists together with analysts and others from the policy community to investigate ways in which technology can enhance international security. Among the various centers within the U.S. and abroad that study international security, our Center for Global Security Research is unusual in its affiliation with a national security laboratory. LLNL is only one of two laboratories in the nation authorized to work on all aspects of nuclear weapons and weapons technology. The Laboratory's broad and deep base of science and engineering expertise, developed in the course of its national security work, can be tapped for Center studies. By supporting independent research that explicitly considers the integration of technology in defense, peacekeeping, arms control, and nonproliferation policy, the Center makes important contributions to national and international security.

This Publication

The articles in this report highlight our work in nonproliferation, arms control, and international security. The majority of these articles describe our proliferation prevention and our response programs. These activities involve extensive collaborations outside the Laboratory, with international organizations on the one hand and with federal, state, and local law enforcement agencies on the other. Our work in the detection and response area and in avoiding surprise involves close partnerships with the defense and intelligence communities, respectively, and thus does not lend itself to much publicity. However, the collection of articles presented here gives an indication of both the complexity of the nonproliferation challenge and the range of LLNL's programs to achieve this critical national security objective.

Commentary by Wayne Shotts

Russian Programs Are Vital to U.S. and Global Security

THE end of the Soviet era dramatically altered the political landscape. In less than a year, President Reagan's "Evil Empire" disintegrated, and for the first time in history, Russia was not ruled by an autocracy. However, the former Soviet republics had virtually no experience with constitutional government. Neither did they have the economic prosperity or political stability that are the foundation of Western-style democracy.

As Russia struggles to turn the idea of democracy into reality, we cannot forget that it is the only country with a nuclear weapons stockpile capable of annihilating the United States. Even though the Russian Duma ratified the bilateral Strategic Arms Reduction Treaty II in April 2000, stockpile reductions will take years to achieve. Clearly, we must continue to address the Russian nuclear reality. But instead of the Cold War approach of developing more nuclear weapons in response to the threat, today's approach is one of engagement and assistance.

The U.S.–Russian programs grew out of reciprocal visits and collaborative experiments in the late 1980s by U.S. and Soviet scientists, coupled with forward-looking planning by the Department of Energy and its national laboratories. Over the past decade, DOE's Russian programs have grown from a handful of informal lab-to-lab contracts to a portfolio of formal activities to reduce nuclear threats and prevent proliferation.

These programs are an integral component of our nation's multilayered nonproliferation strategy. They address the heart of proliferation prevention—arms reduction, protection of weapons-usable nuclear materials, and nonproliferation of weapons know-how.

The arms-reduction programs are the largest effort (approaching a billion dollars per year). Conducted primarily by the Defense Department, they implement formal treaties and agreements aimed at reducing the number of delivery systems, weapons, and warheads and eliminating stockpiles of weapons-usable nuclear material (including material from dismantled warheads). Livermore is involved in work associated with the secure storage facility at Mayak, in monitoring the Highly Enriched Uranium (HEU) Purchase Agreement, and in joint activities for plutonium disposition.

Programs that address the threat posed by weapons-usable nuclear materials comprise the next level of effort (hundreds of millions of dollars a year). Vast quantities of nuclear materials are located, sometimes under less than adequate protection, at many sites across Russia. Together with our sister laboratories, we are working with the Russians to secure these materials in place and to prevent nuclear material from leaving Russia.

At the third level of effort (tens of millions of dollars annually) are programs that address the human aspect of nonproliferation. Lawrence Livermore was instrumental in initiating programs to engage former Soviet weapons scientists in nonweapons research, contributing to their decisions to remain in Russia rather than possibly emigrating to find employment with proliferators. Other programs provide assistance in creating commercially viable regional employment and market opportunities.

In the decade since these programs were initiated, the U.S. has become an even more effective partner with Russia as both countries develop a much more complete understanding of each other's nuclear complex. Joint planning and execution of projects has led to increased trust between U.S. and Russian personnel. As a result, we are being granted access to increasingly sensitive aspects of the Russian nuclear enterprise, and previously inconceivable joint projects are being proposed by the Russians. The downside of this increased openness is the revelation that securing Russia's at-risk nuclear materials and assisting in redirecting the Russian nuclear weapons complex are much larger undertakings than previously thought.

Views of the value of these Russian programs vary widely. In the U.S., the programs are either lauded as an unprecedented opportunity to gain access to Russia's nuclear facilities and essential for national and global security or reviled as excessively expensive and ineffective welfare for Russia. Views in Russia are similarly wide-ranging, where the desire for economic assistance runs counter to fears of spying, exploitation, and loss of national prestige.

Despite rhetoric to the contrary, these programs are beginning to have a real effect in Russia. Large quantities of at-risk nuclear materials have been secured. Thousands of weapons workers are turning to peaceful projects. Transparency is coming into once-dark corners of the Soviet nuclear enterprise. Most important, a foundation of trust has been laid between the U.S. nuclear laboratories and their Russian counterparts—trust that can help address both nations' vital security concerns, today and in the future.

■ Wayne Shotts is Associate Director, Nonproliferation, Arms Control, and International Security.

Preventing Nuclear Proliferation

Livermore experts spend long weeks away from home helping to secure nuclear materials and weapons know-how in the former Soviet Union.

To some observers, the end of the Cold War and sudden collapse of the Soviet Union posed a more dangerous situation than the Cold War itself. The problem was economic and political instability in a region laden with a large number of nuclear weapons, nuclear materials, and nuclear weapons scientists. With the collapse of centrally maintained controls, managing nuclear weapons, materials, and expertise to prevent their transfer to other nations or even terrorists became an urgent task for Russia and the other newly independent states—and an opportunity for the United States to provide assistance.

As Lawrence Livermore Director Bruce Tarter notes, "It is in the interest of the world and the U.S. to work with Russians to contain nuclear weapons, nuclear materials, and nuclear experts within the framework of a stable society." The U.S. Department of Energy and its national laboratories have been given responsibility for developing programs with Russia's Ministry of Atomic Energy (Minatom) and other agencies in the former Soviet Union.

Livermore's Russian programs are concentrated in the Nonproliferation, Arms Control, and International Security (NAI) Directorate, specifically its Proliferation Prevention and Arms Control program. According to physicist William Dunlop, the program leader, Livermore's Russian programs draw upon a wide range of Laboratory strengths, including nuclear materials characterization, radiation detection, forensic science, computer simulation, site security, weapons physics research, and design, testing, and dismantlement.

At nuclear materials storage facilities, weapons laboratories, remote customs sites, and airports and seaports across Russia and the other newly independent states, Livermore men and

The Post–Cold War Challenge

women spend long weeks away from home helping to make nuclear materials and weapons know-how more secure. Despite occasional setbacks—and sometimes difficult negotiations—their progress is a testament to the strong professional relationships they have established with their colleagues in the former Soviet Union.

One telling mark of progress appeared in March when Lawrence Livermore signed the first contract between a DOE laboratory and a Russian nuclear weapons manufacturing plant. The partnership with the Avangard Foundation, an independent Russian business that is the commercial-projects-gathering arm of the Avangard production plant, contracts for the manufacture of kidney dialysis equipment in the closed city of Sarov. Until the 1990s, Western researchers were not allowed to visit the highly secure city; it and other cities like it dedicated to nuclear weapons activities were not even on maps.

Livermore's Russian programs currently take one of two thrusts. The first is enhancing the protection, control, and accounting of weapons-usable nuclear materials and technologies. The second is helping to find new nonweapons job opportunities for the former Soviet weapons scientists. Taken together, these programs address two of the key proliferation concerns in Russia.

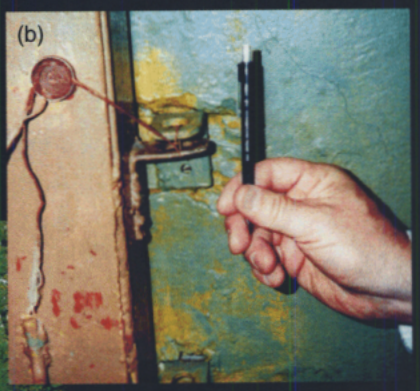
Countering Nuclear Theft

In 1993, the U.S. in partnership with the newly independent states formed a first line of defense against the theft of nuclear materials. The threat is particularly acute in Russia because the Russians have a large number of nuclear storage facilities and nuclear materials producers and exporters but lack an overall system to track or control these materials.

The Material Protection, Control, and Accounting program works with Minatom civil and weapons complexes, the independent Russian civil sector, the Russian nuclear navy, uranium and plutonium storage sites, and reactor and fuel facilities. The program protects against both insider and outsider theft with a host of physical security measures and systems to protect and monitor nuclear materials. Enhancements range from the installation of new fences and modern locks to sensitive radiation detection equipment and sophisticated alarm systems.

In analyzing a site, Livermore experts look for vulnerabilities such as inadequate access control systems and poorly protected building perimeters. For example, doors to vaults holding nuclear materials may have been secured using only wax-and-string seals to detect unauthorized entry. There may be no metal or radiation detectors at entrances to and exits from sensitive areas. Also, areas around facilities may be overgrown and poorly protected by fences and sensors.

Livermore project leader Scott McAllister notes that most U.S. principles, techniques, and tools for nuclear material protection, control, and accounting have been developed by or in conjunction with DOE national laboratories. Livermore personnel apply this longstanding expertise when working with their Russian colleagues. A Livermore employee visiting one of the upgraded sites in Russia would notice many similarities to the equipment and procedures currently used throughout the DOE complex. Examples include access control booths at building entrances, identification badges read by computerized systems to control access to high-security areas, and metal and nuclear material detectors to check people entering and leaving



(a) Before material protection, control, and accounting efforts began, areas around Russian nuclear facilities were, in some cases, overgrown and poorly protected by fences and sensors. (b) Inside, doors to vaults holding nuclear material may have been secured with only wax-and-string seals to detect unauthorized entry.

facilities containing nuclear material. "We're helping the Russians update their old system of 'guards, guns, and gates' with more sophisticated technical systems," McAllister says.

Livermore-aided upgrades are currently in place at many of the more than 300 buildings located at over 50 sites included in the program. These sites include some of the most important nuclear institutes in Russia, such as the All-Russian Scientific Research Institute of Technical Physics in Snezhinsk (formerly known as Chelyabinsk-70), a facility similar to Los Alamos or Livermore.

Livermore people also work with the Northern and Pacific fleets of the Russian Navy to strengthen the protection of highly enriched reactor fuel for nuclear-powered vessels. This work involves direct interactions with the Russian Ministry of Defense to characterize the sites, define the necessary improvements, and help implement upgrades, a situation that would have been inconceivable only 10 years ago. Livermore also manages development and implementation of the Federal Information System project, a comprehensive system for tracking Russia's nuclear material inventory.

A Second Line of Defense

The Russian Federation State Customs Committee must deal with 20,000 kilometers of border to 14 nations, including Iran and North Korea. However, authorities have insufficient funds for equipping customs sites with modern technology to detect illicit nuclear materials trafficking. Since 1997, DOE's Second Line of Defense program has been providing an additional layer of assurance by helping to protect the most important customs control sites and border points in Russia. Says Livermore project manager Jeff Richardson, "We're establishing one more layer of defense that did not exist until very recently."

The program supports the development and installation of Russian-manufactured nuclear detection equipment and provides better training for front-line customs officers. Livermore's capabilities in radiation detection and forensic science are central to these efforts; a team of Russian customs officials and other government representatives visited Livermore in November 1998 and December 1999 for a series of workshops on preventing the smuggling of nuclear materials.

The program has already achieved several key milestones. In 1998, a U.S.–Russian team led by Los Alamos National Laboratory equipped Moscow's Sheremetyvo International Airport with radiation detection equipment, including pedestrian portal monitors for departing passengers. The ceremony commissioning the equipment was part of the U.S.–Russia presidential summit in September 1998. Future airport upgrades will include a cargo monitoring system, a system for improved detection of shielded nuclear materials, and technical training for customs officers.

Also completed in 1998 was the Livermore effort to install pedestrian and vehicle monitoring portals at Astrakhan, a major seaport on the Caspian Sea for shipments to Iran and

(a)

(a) Livermore scientists and engineers helped to design a hardened annex to an existing Russian nuclear material storage bunker. (b) Upgraded facilities often include such modern systems as access control booths.

beyond. The following year, systems for monitoring rail cars were installed, and the development of new training programs began.

The Second Line of Defense has surveyed customs inspection posts at Vladivostok, Vostochniy, Olya, Rostov, and Novorossiysk—all cities situated along Russia's southern and eastern borders—for future equipment upgrades. In 1999, Livermore completed a study prioritizing the remaining customs points and border posts, including those on the Black Sea and the Caspian Sea and those bordering North Korea and Kazakhstan.

In addition, Livermore experts in cooperation with Russian Customs Academy colleagues are developing a training program for customs officers. Under this program, Russian technical experts will instruct students and inspectors on how to use radiation portal monitors and handheld detectors, how to spot anomalies in export documents and manifests, and how to examine containers that might hide nuclear material.

Richardson says a particular technical challenge is detecting and identifying weak nuclear radiation sources such as highly enriched uranium. This year saw the initial development of Russian equipment employing what is known as active neutron interrogation. The equipment will bombard suspected cargoes with neutrons to detect illicit highly enriched uranium shipments.

Warheads Pose Challenges

Ironically, the success of nuclear arms reduction agreements has compounded the problem of monitoring nuclear materials. Both Russia and the U.S. are dismantling thousands of nuclear warheads. In April 2000, Russia's Duma ratified the Strategic Arms Reduction Treaty (START) II that cuts each side's strategic nuclear arsenal to between 3,000 and 3,500 warheads, down from the 6,000 level under START I. (The U.S. Senate ratified START II in 1996.) Future treaties could present several challenges to the West, such as verifying that warheads are in fact being dismantled, that the dismantlement is irreversible, and that the nuclear materials separated from the weapons are accounted for and secure.

Many of Livermore's warhead dismantlement activities support the 1997 Helsinki summit accords. Presidents Clinton and Yeltsin declared then that each country would remove 50 metric tons of plutonium from its nuclear weapons program and ensure that the material could never again be used in weapons. The June 2000 U.S.–Russian Moscow summit builds upon the Helsinki agreements by specifying the plans, schedules, and methods for making 34 metric tons of plutonium inaccessible for use in nuclear weapons.

The International Atomic Energy Association (IAEA) is expected to have responsibilities for monitoring this plutonium. Livermore experts are helping to establish the U.S.–Russian–IAEA inspection system for the plutonium that is scheduled to be stored at the Mayak facility in the Ural Mountains. The U.S. is providing $400 million in goods and services toward construction of this storage facility, which is scheduled for completion in 2003. The U.S. has proposed using advanced detection systems that will verify, without revealing classified information, that the plutonium arriving at Mayak came from dismantled nuclear weapons. Jim Morgan, leader of Livermore's Radiation Technology Group, says that the detection system

(a) Cars and (b) trains leaving and entering Astrakhan on the Caspian Sea are monitored for nuclear materials.

will be demonstrated to Russian experts at Los Alamos National Laboratory this fall. The meeting will be a follow-up to a joint workshop that was held at Livermore in 1997 to demonstrate high-resolution gamma-ray spectrometry for analyzing weapons-grade plutonium.

Livermore scientists also participate in DOE's Lab-to-Lab Warhead Dismantlement Transparency program. This effort encourages Russian and American dismantlement experts to discuss ways to improve transparency through measures increasing confidence that agreed-to actions are taking place. Livermore is responsible for developing transparency measures for the conversion in Russia of 500 metric tons of highly enriched uranium from dismantled nuclear warheads to low-enrichment uranium. The U.S. is purchasing the converted uranium to fuel its civil nuclear power reactors. The highly enriched uranium effort is currently managed by Livermore's Energy Programs Directorate in close cooperation with the NAI Directorate.

Laboratory experts are also involved in negotiations with Russia to convert its three remaining weapons-grade plutonium production reactors to civil use (the U.S. has ceased producing weapons-grade plutonium). In return, the U.S. is allowed to monitor the 14 metric tons of weapons-grade plutonium oxide produced at the reactors from January 1, 1997, until the reactors are converted.

Disposing of Plutonium

Russia has long considered weapons-grade plutonium recovered from its intermediate products and wastes to be too important a national resource for permanent immobilization, which would ensure that it could never again be used for weapons. Their standard practice is to reprocess all plutonium-containing wastes and recycle the plutonium for their weapons program or as mixed oxide (MOX) fuel for reactors.

In contrast, the U.S. has decided on a dual-track approach. Relatively clean plutonium will be used for MOX reactor fuel, while impure plutonium will be immobilized. In the immobilization approach, plutonium is one constituent of a ceramic waste form, with a neutron-absorbing material added to the ceramic to prevent a nuclear chain reaction during long-term storage in a geologic repository. The plutonium-containing ceramic is sealed inside cans, the cans are placed in a stainless-steel canister, and the canister is filled with molten glass containing high-level defense wastes to further increase the plutonium's inaccessibility.

Livermore scientists are leading the DOE program to develop U.S. immobilization technology. They have also been encouraging their Russian colleagues to consider immobilizing some of their plutonium. Russian scientists are familiar with the concept. Since 1995, Russian scientists have toured Livermore's plutonium facility on six occasions (most recently in July 2000) to learn more about immobilization techniques.

Led by engineer Les Jardine, a Laboratory team has successfully encouraged Minatom officials to proceed with research and development, engineering, and system analysis for immobilizing a portion of its plutonium inventory. This plutonium would come from materials, residues, and wastes with concentrations higher than 200 parts per million. "We showed the Russians that it makes more economic sense to immobilize rather than reprocess some of their plutonium," says Livermore's Lee MacLean.

The current objective is to develop a Russian capability for industrial-scale immobilization of plutonium by 2005. Over 30 contracts have been placed with Russian institutes. The contracts include engineering feasibility studies at the Krasnoyarsk and Mayak industrial sites and research efforts at Russian scientific institutes to develop glass and ceramic immobilization forms. Russian and U.S. scientists have also defined the nonproliferation safeguards needed to prevent terrorists from retrieving the plutonium from its immobilized form.

In May, Lawrence Livermore received a plutonium oxide saltwasher it had purchased from the Russian Scientific Research Institute of Atomic Reactors. Once adapted to U.S. electrical

Livermore experts are helping to upgrade the training of Russian customs officers to detect illicit trafficking in nuclear materials or related equipment.

standards, the machine will be tested at Livermore's plutonium facility, where it is expected to provide a more efficient method for preparing U.S. plutonium for immobilization.

According to Jardine, the equipment "shows that their technical people are extremely competent and are capable of efficiently handling plutonium fissile materials."

Test Ban Treaty Collaborations

Livermore scientists are involved in a host of interactions with Russia in the context of the Comprehensive Test Ban Treaty (CTBT). Livermore teams support the U.S.–Russian CTBT Monitoring and Verification Working Group and collaborate on research projects related to the treaty, including on-site inspection measures.

Although not yet ratified by all participants, the treaty, which forbids all nuclear detonations, creates an international monitoring network to search for evidence of clandestine nuclear explosions. Livermore and Russian scientists are documenting how regional geology would affect the transmission of seismic signals from low-yield underground nuclear tests. They are also working to differentiate the seismic signals of a clandestine underground nuclear test from those of a mining blast or earthquake.

An allied effort is the On-Site Inspection program, which supports the CTBT Preparatory Commission in Vienna by defining the technologies, procedures, and equipment that would guide on-site inspections. Under terms of the treaty, a nation suspecting another of conducting a nuclear test may request an on-site inspection to determine the nature of an ambiguous event. The inspections must be conducted quickly in order to collect information about short-lived phenomena, such as seismic aftershocks, that are produced by an underground nuclear explosion.

A major milestone occurred in October 1998 when a joint on-site inspection exercise was conducted at Snezhinsk, Russia. The exercise played out the first 15 days of a hypothetical on-site inspection. In the exercise, separate U.S. and Russian inspection teams analyzed simulated data from visual, seismic, and radionuclide sources.

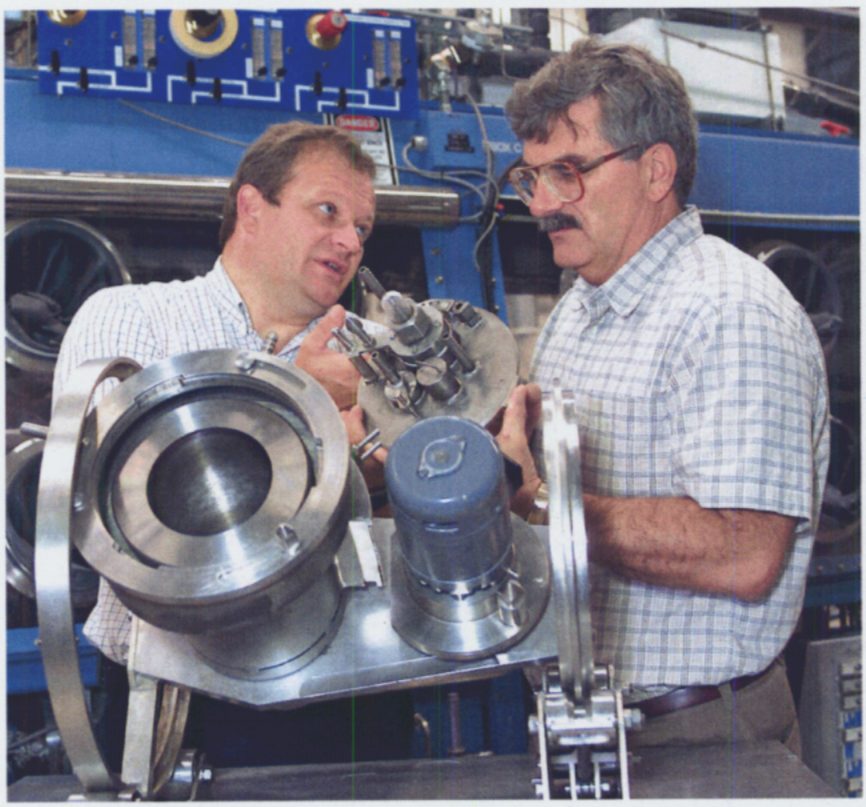
A second exercise was successfully completed in April 2000, again in Snezhinsk. Livermore geologist Jerry Sweeney says that this exercise was even more cooperative than the first because inspection teams were composed of both Russians and Americans. "The exercise was valuable because we saw how an international inspection team might function," he says.

Livermore is also collaborating on several CTBT-related research projects sponsored by the International Science and Technology Center. One project is investigating electromagnetic signals accompanying underground chemical explosions as a way to enhance the discrimination between chemical and nuclear explosions.

Another project is using powerful mechanical seismic vibrators to produce 1- to 8-hertz waves that can be detected at distances of up to 500 kilometers. The goal is to determine if the semiportable vibrators (essentially a railroad tank car placed on end, combined with an air bladder to shift water at a given frequency) can cost-effectively substitute for large explosion sources that are commonly used to calibrate regional CTBT monitoring stations.

Keeping Expertise at Home

Two DOE programs, the Initiatives for Proliferation Prevention and the

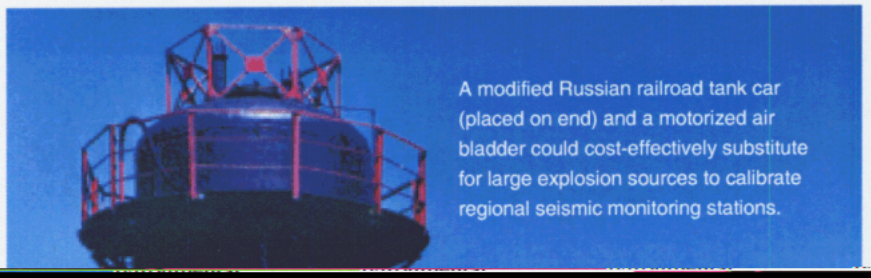


Livermore's Mark Bronson (left) and Les Jardine examine the Russian-designed and built plutonium oxide saltwasher that is being tested for use in the U.S. plutonium disposition program.

Nuclear Cities Initiative, focus on preventing the movement of technical knowledge and expertise from the former Soviet nuclear weapon complex to other nations or terrorist organizations. Both programs attempt to develop self-sustaining nonweapons-related work for former nuclear scientists, engineers, and technicians and introduce the basic principles of market economics and Western business practices.

Founded in 1994, the Initiatives for Proliferation Prevention (IPP) promotes collaborative projects among DOE's national laboratories, U.S. industry partners, and 170 institutes in the newly independent states. The goal is to attract investment by U.S. companies that will lead to self-sustaining business ventures and provide long-term employment opportunities for former Soviet weapons workers.

The approach involves three steps. First, Livermore works with weapons scientists and institutes to identify and evaluate the commercial potential of research and development activities at the institutes. Second, partnerships are formed with U.S. industry, and DOE shares the investment costs. During the final phase, U.S. industry and the institutes continue the commercial relationship without DOE participation.



A modified Russian railroad tank car (placed on end) and a motorized air bladder could cost-effectively substitute for large explosion sources to calibrate regional seismic monitoring stations.

Project leader Ted Saito says that Lawrence Livermore's longstanding knowledge of those institutes, its people, and their capabilities makes the Laboratory an excellent facilitator for U.S. companies. Livermore scientists and engineers bridge communication gaps and contribute to the evaluation of technical and economic potential by U.S. companies that consider creating ventures with Russian partners.

About 1,100 scientists from the former Soviet Union have been or are currently working on Lawrence Livermore IPP projects in the areas of materials science and manufacturing, optics and lasers, environmental

says, "The Russians are sharp technical people and their processes offer a lot to Western companies." He notes, however, that collaborations with U.S. industry must overcome a weak Russian business infrastructure and export controls that make shipping materials in and out of Russia difficult.

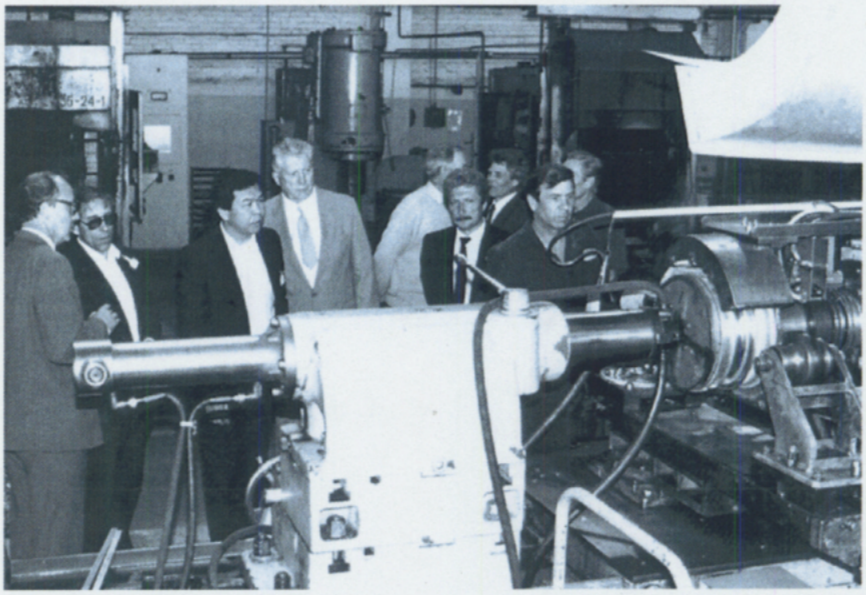
Nuclear Cities Focus

Whereas the IPP focuses on commercial developments with institutes in several countries of the former Soviet Union, the Nuclear Cities Initiative (NCI), formed in 1999, is helping former weapons experts in Russia's 10 closed nuclear cities make the transition to civilian employment. The closed cities (where Soviet nuclear weapons were designed and manufactured) were completely supported by the old Soviet system. Because of economic hardship throughout Russia, these cities currently receive little government support. What's more, their nuclear institutes are being downsized by Minatom.

The program's initial focus is on three cities: Sarov, Snezhinsk, and Zheleznogorsk. Livermore is concentrating much of its efforts at Snezhinsk, home to Russia's second nuclear weapons design laboratory and sister city to Livermore, California.

Livermore experts are working to create jobs by helping to form new businesses or enhance existing industries, including medical technologies and optical-fiber production. "The goal is to develop business approaches that have a reasonable chance of success with a modest NCI investment," says Livermore NCI leader Paul Herman.

A parallel goal is to create businesses that meet the needs of the global marketplace. Success requires the active participation of foreign industrial partners, for whom Livermore provides an important link to Russians cut off from current trade practices in democratic countries.



Livermore engineers Don Lesuer and T. G. Nieh (second and third from left) are shown with Russian colleagues as they inspect machines used for superplastic forming of automobile wheels. The process could find considerable use in the West.

Kevin Blackwell, a Livermore engineer (left), and Vladimir Zadorozhny, a communications specialist at All-Russian Institute of Technical Physics in Snezhinsk, Russia. Livermore specialists are helping to develop an open computer center at Snezhinsk to provide ready access to customers inside and outside Russia.

The well-publicized contract to begin production of kidney dialysis equipment is only one of several success stories as the program gains momentum. Livermore also signed two NCI contracts in Moscow last March. The first is for developing explosive charges for oil well casings to allow oil to flow effectively at selected depths. The second is for manufacturing a type of multiple mode optical fiber that is used in local area networks.

Livermore and the All-Russian Research Institute of Technical Physics have also agreed to form an open computer center at Snezhinsk for commercial software contracts for Western companies.

Building on the sister-city relationship, teams of Laboratory scientists and potential private-sector partners have visited Snezhinsk to explore new health-care business proposals. Possible areas of research include remote electrocardiograms, x-ray tomography, laser surgery, ultrasound for kidney stones and prostate treatment, ultraviolet blood treatment, and neutron cancer therapy.

California Representative Ellen Tauscher visited Snezhinsk in August 1999 to explore ways in which Laboratory and business leaders in the greater San Francisco Bay Area could help Russia's closed cities create sustainable jobs. "People here in Russia acknowledge that the way for Russia to emerge as an economic force is to build on the shoulders of these very talented and experienced scientists," she says.

The Right Thing to Do

By engaging thousands of former Soviet weapon scientists and enhancing the security at dozens of nuclear materials facilities, Livermore programs have made important progress in helping to prevent nuclear proliferation. Dunlop says that much of that progress has been built upon strong professional relationships with colleagues in the former Soviet Union. In nurturing increasing and effective dialogue with scientists and government officials, Livermore people are also helping to develop the more open atmosphere that is the hallmark of a democratic society.

The Russian Programs Assessment Committee, headed by former Air Force Secretary Thomas Reed, was given the task of reviewing the effectiveness of Livermore's Russian programs. "The Russian programs at Lawrence Livermore National Laboratory are the right things to do," the committee reported in its May 2000 report. "The possibility of nuclear weapons, materials, and expertise leaking out of Russian government control is one of the most horrifying threats facing mankind today. In working to contain that threat, Lawrence Livermore National Laboratory is earning the respect of the national security community."

The committee concludes that "these programs are beginning to have an impact in Russia. Materials have been secured, nuclear experts are turning to peaceful work, and transparency is coming slowly into once-dark corners of the Soviet nuclear empire. More importantly, however, these programs have created a foundation of trust between the U.S. weapons laboratories and their Russian counterparts that can help address both nations' vital national security concerns in the future."

—Arnie Heller

Key Words: All-Russian Research Institute of Technical Physics; Avangard Foundation; Comprehensive Test Ban Treaty (CTBT); highly enriched uranium; Initiatives for Proliferation Prevention (IPP); Mayak, Minatom; mixed oxide (MOX) fuel; Nuclear Cities Initiative (NCI); Material Protection, Control, and Accounting program; Proliferation Prevention and Arms Control program; plutonium; Sarov; Snezhinsk; Strategic Arms Reduction Treaty (START); warhead dismantlement.

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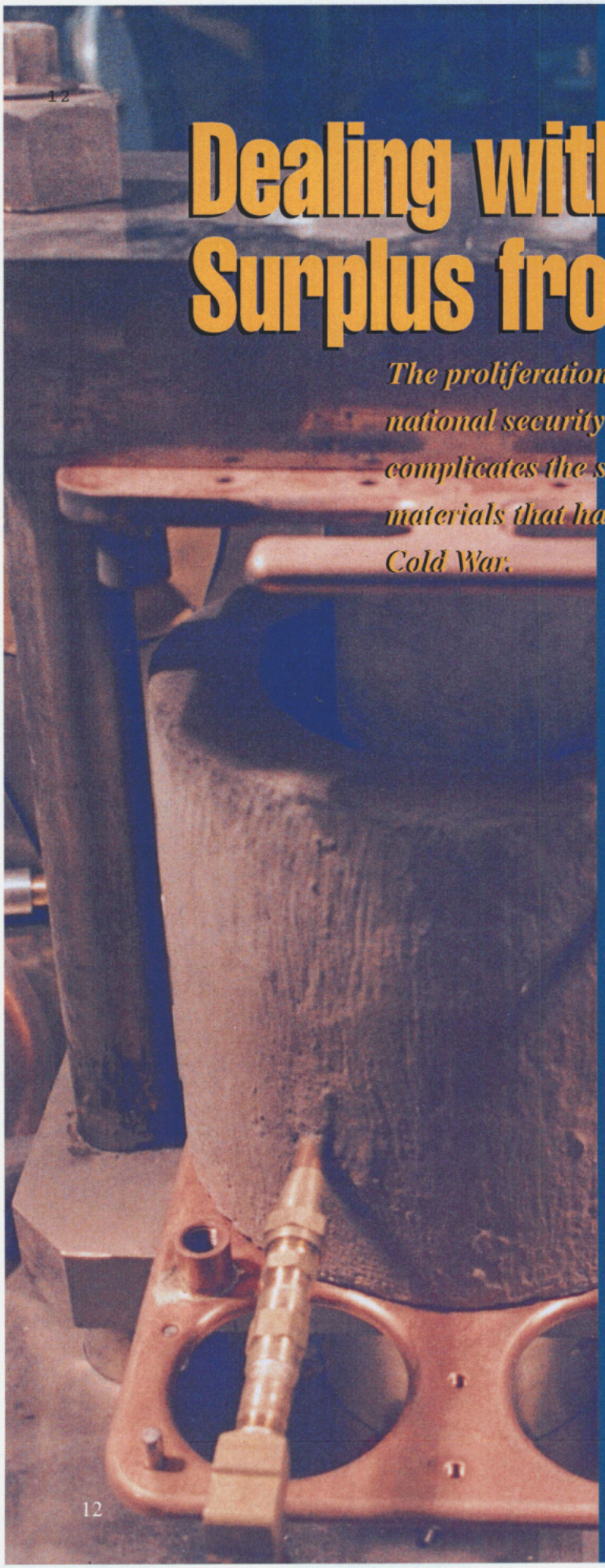
About the Scientist

WILLIAM DUNLOP received his B.A. from the University of Pennsylvania in 1967 and his M.S. and Ph.D in physics from the University of California at Los Angeles in 1968 and 1971, respectively. He joined Lawrence Livermore in 1972 as a physicist in the Special Projects program. From 1976 to 1985, he served as project manager and, later, program manager of various missile and weapons projects. Then for five years, he was a division leader overseeing work on thermonuclear weapons development.

Dunlop became interested in arms control work in 1979 when he was part of the U.S. delegation to the Conference on Disarmament in Geneva. In 1988 and 1989, he was a member of the U.S. delegation to the nuclear testing talks in Geneva. And from 1994 through 1995, Dunlop served as technical advisor to the U.S. Ambassador to the Geneva Conference on Disarmament, during which the Comprehensive Test Ban Treaty was negotiated. In 1990, he became leader of Livermore's Arms Control and Treaty Verification program (recently renamed the Proliferation Prevention and Arms Control program).



Dealing with a Dangerous Surplus from the Cold War

The proliferation of nuclear materials is a threat to national security and world peace. This threat complicates the safeguarding and management of fissile materials that have become surplus since the end of the Cold War.

TEARING down the Berlin Wall in 1989 symbolized the end of the Cold War. However, the real work of ending the Cold War—sharply reducing the number of nuclear weapons—remains to be done.

The governments of the United States and Russia have taken the first steps toward nuclear arms reduction by negotiating the Strategic Arms Reduction Treaties. Under START I, which was ratified in 1991, both countries agreed to reduce their large nuclear weapons arsenals to approximately 6,000 warheads and have already begun to do so by dismantling between 1,300 to 2,000 weapons each year. START II, when it is ratified, will reduce the numbers further to between 3,000 and 3,500.

The dismantling of weapons and the cessation of new nuclear weapons manufacturing, while positive for world peace, have raised a problem: what to do about the fissile materials recovered from the weapons or in inventories that will remain unused. These materials—primarily plutonium and highly enriched uranium—are environmental, safety, and health concerns. But of more urgency is the threat they pose to national and international security if they fall into the hands of terrorists or rogue nations. As arms reduction continues and amounts of surplus fissile materials increase, the potential for such security breaches will increase.

As part of bilateral nuclear nonproliferation work, both the U.S. and Russia have initiated scientific studies to find a way to dispose of surplus fissile materials. In the U.S., the Department of Energy is the technical lead for the disposition studies, acting as a member of the Interagency Working Group of the White House Office of Science and Technology. In this capacity, DOE has mandated separate studies for disposing of plutonium and highly enriched uranium, because of their different chemical characteristics. Lawrence Livermore is focusing primarily on the study of plutonium disposition.

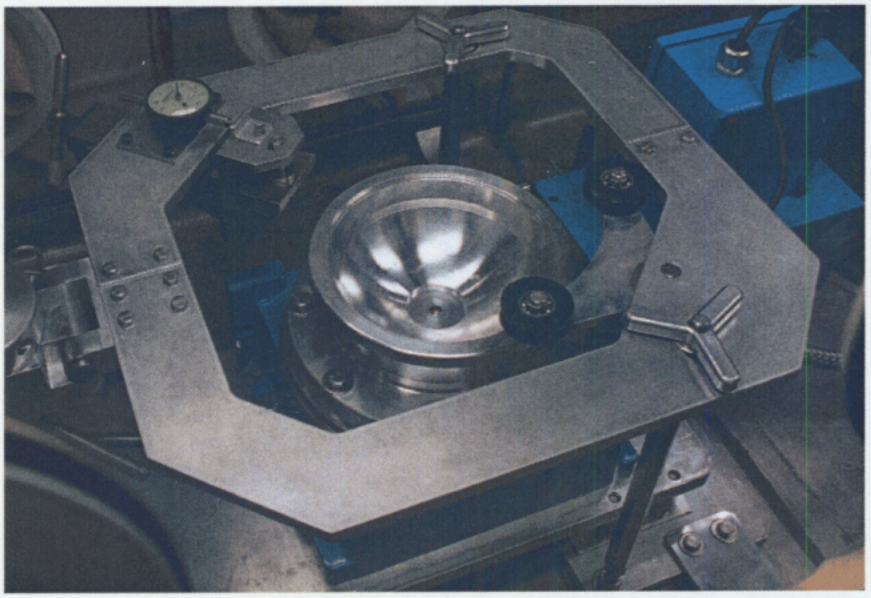


Figure 1. The prototype bisector was designed and tested at Livermore. Using a chipless cutting wheel, it can separate weapon pits into two half-shells in less than 30 minutes so that the plutonium in them can be recovered for disposition.

Plutonium Disposition

After a series of studies, including technical work for a preliminary environmental impact study, DOE selected three reasonable plutonium disposition alternatives for further study: using plutonium as reactor fuel; encasing it in other material, thereby immobilizing it and making it inaccessible; and burying it in a deep borehole.

Lawrence Livermore is involved in studying the front-end processes required to prepare plutonium for disposition and is performing research and development on two of the three specific disposition methods to determine their viability. Specifically, Lawrence Livermore is working with Los Alamos National Laboratory on a system for disassembling weapon pits (or cores, where detonation takes place), recovering the plutonium in them, and converting it into a disposable form. Livermore has also led the two teams studying the immobilization alternative and the deep burial alternative. Oak Ridge National Laboratory is studying the reactor-fuel alternative.

The *Programmatic Environmental Impact Statement* for plutonium disposition was published in December 1996. In January 1997, DOE announced its Record of Decision on plutonium disposition, recommending a dual disposition path: immobilize low-grade plutonium materials and use high-grade plutonium materials to fuel reactors. The alternative of burying surplus plutonium in a deep borehole ran into siting and licensing difficulties and was eliminated from consideration, despite the fact that Livermore studies proved it to be as technically feasible as the other two alternatives.

Recovery and Conversion

Lawrence Livermore and Los Alamos are designing a plutonium recovery and conversion system, the Advanced Recovery and Integrated Extraction System (ARIES). ARIES has five modules, which are used for: pit disassembly, converting plutonium into an oxide (for disposition), converting plutonium into a metal (for long-term storage), packaging plutonium for storage, and performing nondestructive assay to account for plutonium quantities. Lawrence Livermore is focusing on the first two modules.

Pit Disassembly

The pit disassembly, ARIES' first module, consists of a glovebox in which the weapon pit is received; remote handling devices that transfer pits onto a scale for weighing and then move them on to be inspected and have any appurtenant devices removed; and a bisector (Figure 1) that separates the pit into two half-shells by using a chipless cutting wheel. The bisector framework remains stationary while the pit is rotated.

The bisector design takes into account the dimensions, encapsulation methods, construction materials, and manufacturing techniques of these pits in order to incorporate the representative configurations that will be processed through ARIES. It also calls for a "no-hands-on" process to keep radiation exposures to the operator within acceptable limits.

Bisector improvements are being made and will be tested during 1997.

Producing Plutonium Oxide

To be suitable for most of the disposition methods, plutonium must first be converted into plutonium oxide, the job of ARIES's second module. Lawrence Livermore has been developing pyrochemical techniques to accomplish this conversion using various hydride/oxidation (HYDOX) reactions. Three such processes are being researched, all based on reactions in which pure hydrogen gas is used to remove plutonium from a pit by forming a plutonium hydride. The formation of the hydride causes the plutonium to break up into small particles and separate from the other pit materials. The plutonium hydride is collected and then converted to plutonium oxide either directly or after conversion to plutonium nitride.

The experiments on the HYDOX processes seek to minimize production cycle times and maintain safety while producing oxide particles to the required disposition specifications, particularly the more stringent specifications for oxide fuels used in reactors.

A prototype HYDOX furnace has been designed, assembled, and installed and is being used to test the various process options. An additional unit (Figure 2) is being assembled in a glovebox and will be installed and operated at Los Alamos as part of the ARIES demonstration.

The Spent Fuel Standard

Because most nations and even some terrorist groups are technically capable of converting surplus plutonium into nuclear weapons, the ideal disposition method eliminates the possibility of surplus plutonium being used for weapons. If a disposition method is not available within a reasonable time frame, the growing volume of plutonium surplus will make proliferation easier and render arms-reduction agreements meaningless.

Because total elimination is not a practical objective, a National Academy of Sciences study, commissioned by DOE's Office of Nuclear Energy, proposed the next best thing: minimized accessibility. Dubbed the "spent fuel standard" and accepted as the goal of plutonium disposition efforts by the U.S., Russia, and the seven other stakeholder nations, it defines "minimized accessibility" as equivalent to the accessibility of the plutonium found in spent reactor fuel. The spent fuel standard is a reasonable goal because the technology to accomplish it appears achievable within 10 years and implementation can be completed within 25 years. It is also a practical goal because, by definition, it excludes spent fuel plutonium—which comprises the larger part of the surpluses—from disposition and concentrates on weapons-grade plutonium.

The Immobilization Task

Lawrence Livermore is researching plutonium immobilization with the Savannah River Technology Center, Argonne National Laboratory, and Pacific Northwest National Laboratory. Several U.S. universities and private industries are also partners, as are several other nations (including Australia, the United Kingdom, France, and Russia) with interest and experience in immobilization.

Immobilization technology achieves the spent fuel standard by encapsulating plutonium inside a waste form specifically tailored for this function, adding a radiological barrier to increase inaccessibility to the plutonium, and sealing the resulting material inside a stainless-steel canister. Like spent reactor fuel, these canisters would be stored for an interim period before being placed inside a geologic repository. The size, weight, composition, and radiation barrier of the filled canister are intended to make the plutonium in it roughly as difficult to steal and recover as the plutonium in spent fuel.

Before the immobilization alternative can be fully developed and implemented, three decisions need to be made:

- What waste form is to be used for encapsulating the plutonium and what technology is to be used for encapsulation?
- Is the radiological barrier to be internal, that is, mixed with the plutonium, or external, in a separate container that surrounds the plutonium container?
- Where will the plutonium immobilization take place?

Immobilization Options

A great deal of information about stabilizing radioactive material by embedding it in another material has been published. An extensive literature search identified 45 forms considered previously for immobilizing radioactive waste.

These 45 forms were subjected to a formal, two-step screening process to derive top candidates for comprehensive technical evaluation. The two top-

Figure 2. To be suitable for most disposition methods, the excess weapons plutonium must first be converted into plutonium oxide by various hydride/oxidation (HYDOX) methods. The prototype HYDOX furnace design originated at Livermore and has been used to test various HYDOX process options. Livermore technicians William Kuhl (left) and Terry Ludlow assemble a HYDOX furnace in a glovebox. The unit will be used for further testing at Los Alamos National Laboratory.

ranking forms were borosilicate glass and Synroc (synthetic rock), a ceramic material developed by scientists at the Australian National University, Lawrence Livermore, and Savannah River.

The glass and ceramic forms were evaluated in five variations of the immobilization process to look at various permutations of forms, radiological barrier concepts, and facilities in which the work could be done. As in all other disposition methods, the plutonium must first be converted into an oxide, and then a neutron absorber mixed with it for criticality control.

Three Glass Variations

Variation 1: Internal Radiation Barrier. In this two-stage process, plutonium oxide reacts with glass frit containing a neutron absorber to prepare a plutonium–neutron-absorber–glass frit (Figure 3a). First, 4 kilograms or less of plutonium as plutonium oxide are combined with neutron absorber and glass frit to form plutonium–glass frit.

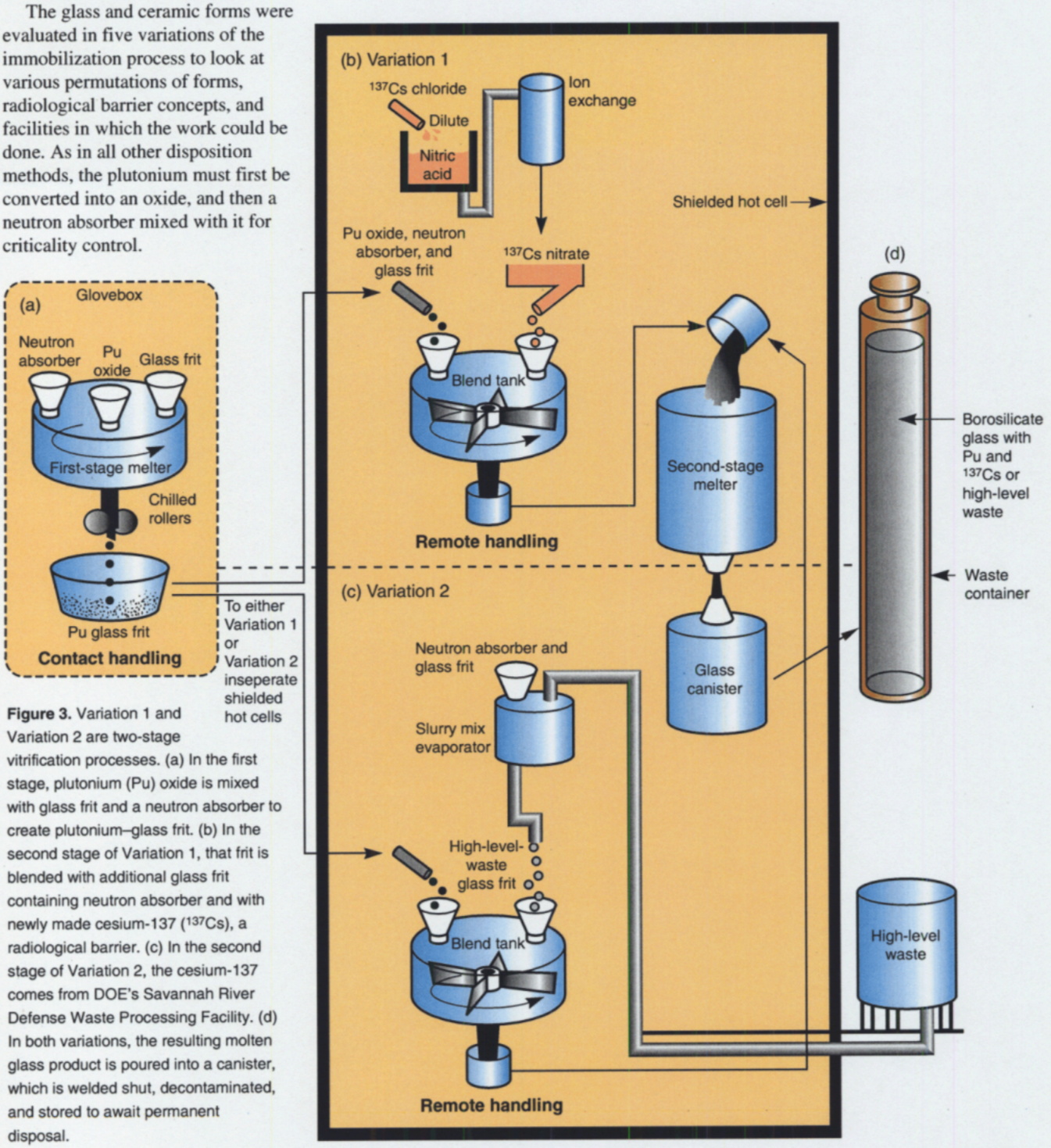


Figure 3. Variation 1 and Variation 2 are two-stage vitrification processes. (a) In the first stage, plutonium (Pu) oxide is mixed with glass frit and a neutron absorber to create plutonium–glass frit. (b) In the second stage of Variation 1, that frit is blended with additional glass frit containing neutron absorber and with newly made cesium-137 (^{137}Cs), a radiological barrier. (c) In the second stage of Variation 2, the cesium-137 comes from DOE's Savannah River Defense Waste Processing Facility. (d) In both variations, the resulting molten glass product is poured into a canister, which is welded shut, decontaminated, and stored to await permanent disposal.

The second step (Figure 3b) blends batches of 50 kilograms or less of plutonium as plutonium–glass frit with additional neutron-absorber-containing glass frit and cesium-137, where the cesium is used as a radiological barrier. The resulting molten glass product is poured into a canister, which is welded shut, decontaminated, and stored until permanent disposal in a high-level waste repository (Figure 3d).

Variation 2: Internal Radiation Barrier. This two-stage process is similar to Variation 1 but would use existing, modified facilities. The first-stage melt of plutonium oxide and borosilicate frit (containing a neutron absorber) is made in an existing facility at Savannah River, and the second-stage melt (Figure 3c), which incorporates the cesium radiological barrier, will be done at a new melter to be built next to Savannah River's Defense Waste Processing Facility. The high-level-waste fission product cesium-137 will come from the Savannah River tank farms.

Variation 3: External Radiation Barrier. This is a "can-in-canister" concept in which plutonium is immobilized in borosilicate glass that contains a neutron absorber. Then the mixture is poured into cans, which are in turn placed in canisters into which molten high-level-waste glass is poured (Figure 4). The high-level-waste glass comes from the Defense Waste Processing Facility at Savannah River.

Two Ceramic Variations

Variation 4: Internal Radiation Barrier. Plutonium oxide is first converted to plutonium nitrate and then

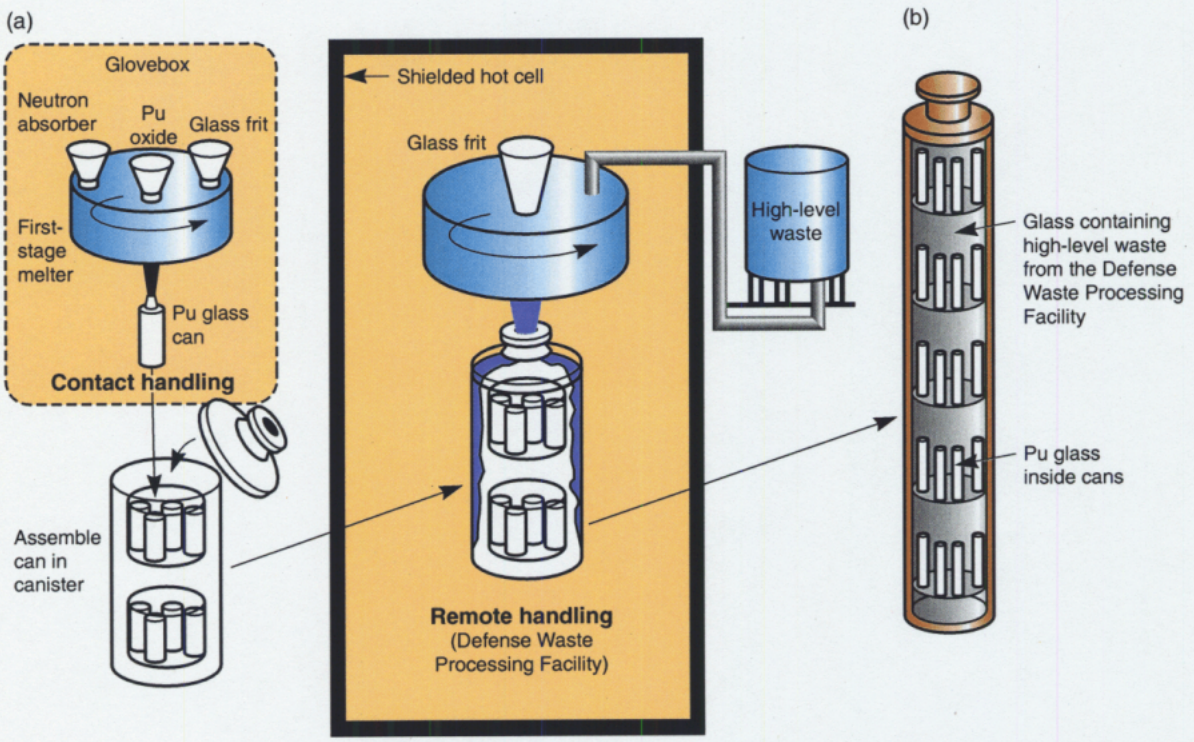


Figure 4. (a) Vitrification Variation 3 is a "can-in-canister" concept in which plutonium (Pu) immobilized in borosilicate glass is poured into a can, which is then placed in (b) canisters into which molten high-level-waste glass from the Defense Waste Processing Facility at Savannah River is poured. The outer canister provides an external radiation barrier.

blended with mineral-forming oxides (ceramic precursors), a neutron absorber, and a titanate that contains cesium. The mixture is calcined (heated but not fused), loaded into bellows, and hot pressed into a dense form (Figure 5). Twenty of these forms are loaded into a canister and packed with titanium oxide granules. The canisters are stored until they can be sent to a high-level-waste repository.

Variation 5: External Radiation Barrier. This is a can-in-canister approach similar to Variation 3. The ceramic form is made by blending plutonium oxide with ceramic precursor materials and a neutron absorber. The mixture is calcined, cold pressed, and sintered (heated but not melted) into a dense form that is loaded into small cans. The small cans are put inside a storage canister, where they are surrounded by glass made with high-level waste (Figure 6).

Progress Report

For the five process variations, the task team developed process flowsheets and preconceptual plant designs; gathered the required environmental data; and determined the workforce, cost, and schedule requirements for implementing them.

At the end of these tasks, the team recommended the can-in-canister concept to DOE and has proceeded to the research and development stage to determine whether glass or ceramic should be the immobilization form. Research on vitrification forms is being done with Savannah River, Pacific Northwest, and Argonne laboratories,

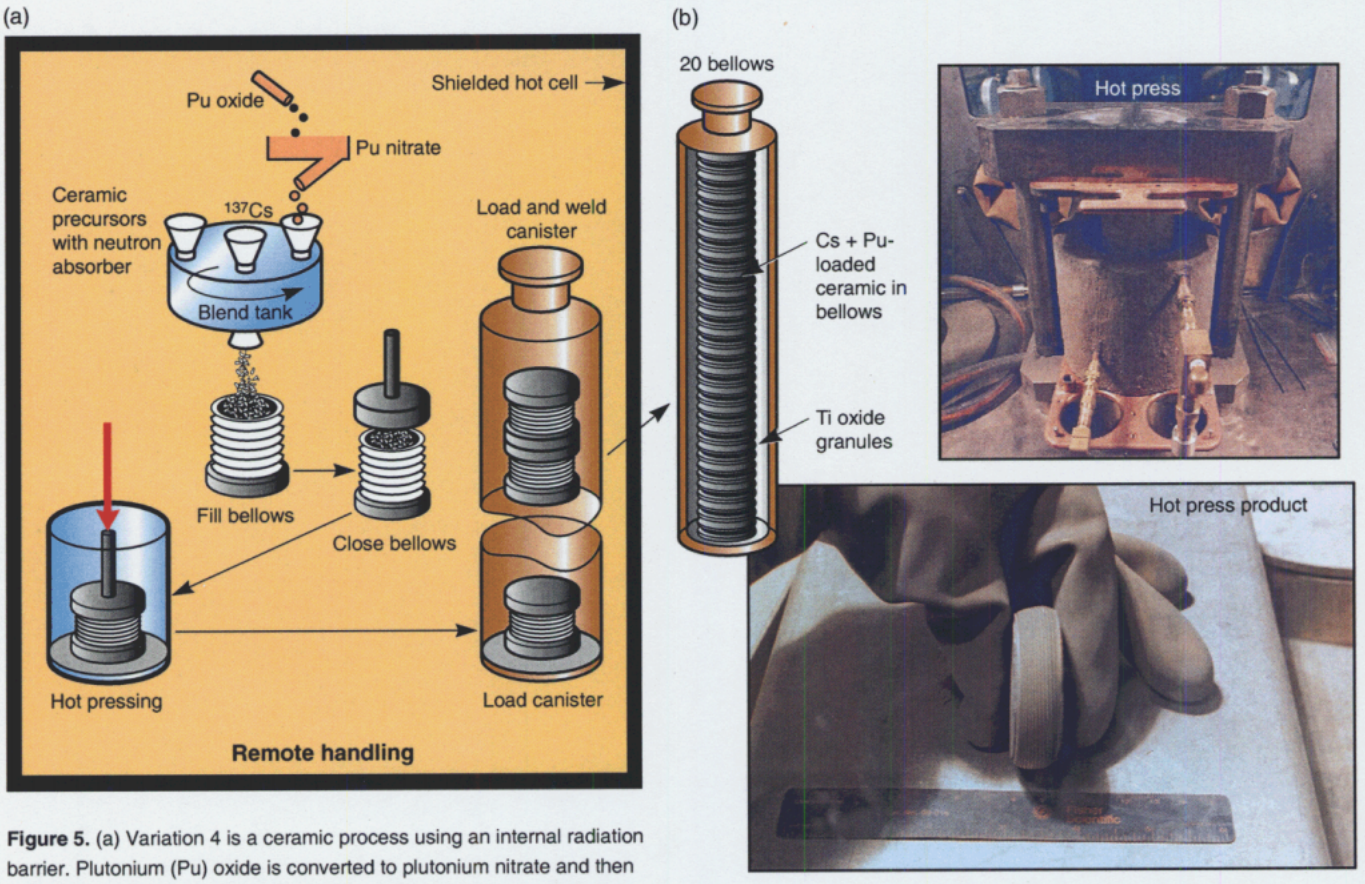


Figure 5. (a) Variation 4 is a ceramic process using an internal radiation barrier. Plutonium (Pu) oxide is converted to plutonium nitrate and then blended with mineral-forming oxides (ceramic precursors), a neutron absorber, and a titanate-containing cesium (Cs). The mixture is heated, loaded into bellows, and hot pressed into a dense form. The hot press is in the photo, upper right; the dense-form product is pictured lower right. Twenty of these products will be loaded into (b) a canister, packed with titanium (Ti) oxide granules, and sent, ultimately, to a permanent high-level-waste repository.

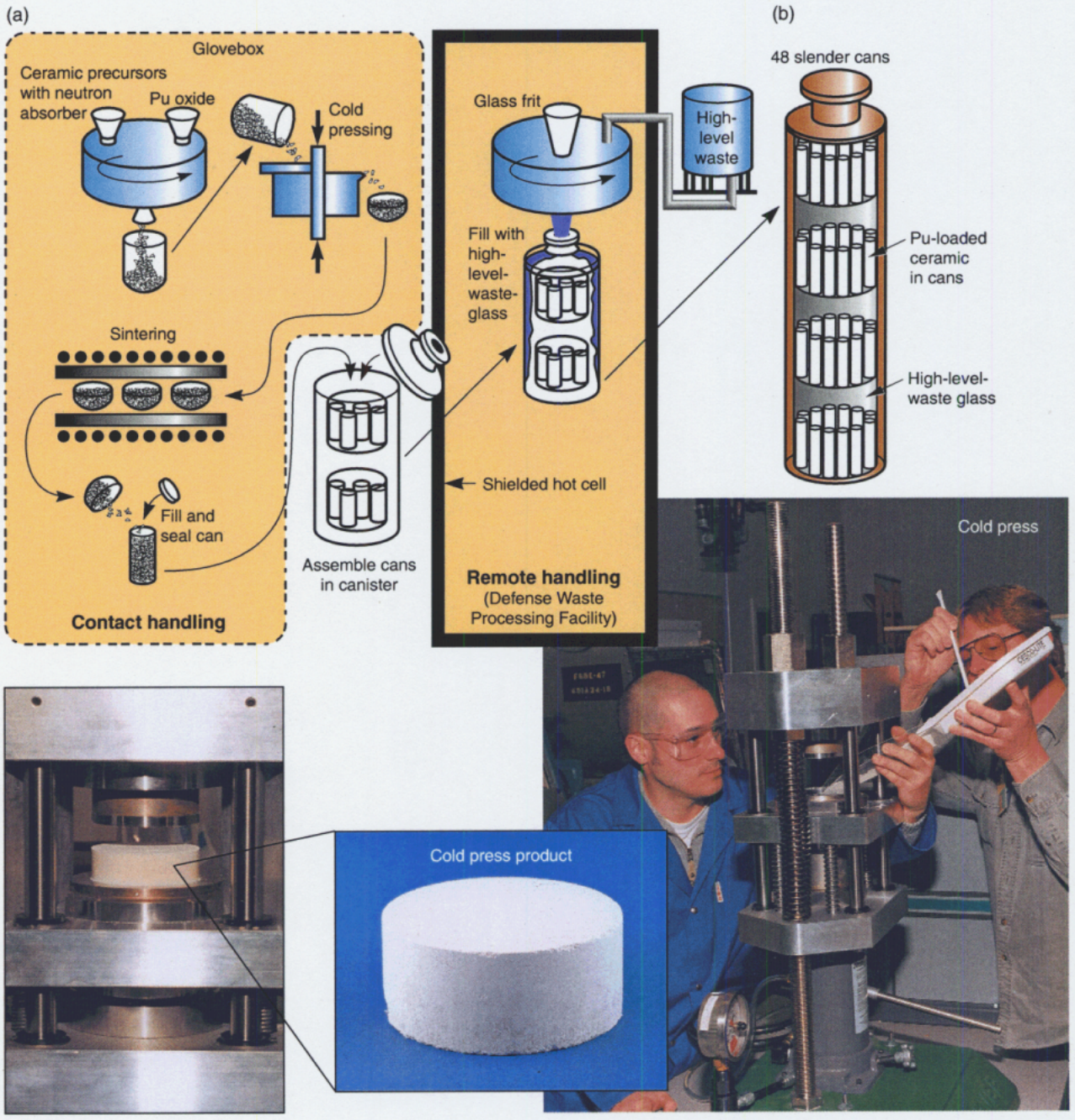


Figure 6. (a) Variation 5 is also a ceramic process, but it involves a "can-in-canister" (or external-radiation-barrier) approach like Variation 3. The ceramic form is made by blending plutonium (Pu) oxide with ceramic precursors and a neutron absorber. The mixture is heated, cold pressed, and sintered (heated but not melted) into a dense form. The cold press is in the photo, lower right; the dense-form product is pictured lower left. The ceramic product is loaded into small cans, which are put inside (b) a storage canister and surrounded by glass made with high-level waste.

while the Australian Nuclear Science and Technology Organisation (ANSTO) and Savannah River are Lawrence Livermore's partners in ceramic form research.

Desirable Glasses

All the ways to use glass to immobilize plutonium require further research into improving the solubility of plutonium in the glass melts, determining the most effective neutron absorber, understanding solubility interactions between the neutron absorber and plutonium, and analyzing how impurities affect the quality of the waste form. Glass-forming chemicals must be formulated to dissolve the greatest amounts of plutonium oxide, neutron absorber, and any uranium and other impurities present. Moreover, these chemicals should have the best processability and chemical durability characteristics. Finally, to prevent leaching, the glass product they form should ideally be homogeneous, with no separated crystalline or amorphous phases.

Two new candidate glasses have been formulated. The first, an alkali-tin-silicate (ATS) glass formulated at Argonne National Laboratory, was to be used in the process in which cesium would be an internal radiation barrier. However, because the preferred immobilization process appears to be the can-in-canister concept, work on this glass stopped.

A second glass formula, proposed for use in the can-in-canister process variation and now the preferred formulation for vitrification, produces glass similar to commercial Löffler optical glasses that contain 55% by weight or less of rare-earth oxides. (Because this glass requires a very high operating temperature, highly volatile cesium cannot be used as an internal radiation barrier.) The chemistries of actinides (the chemical family of plutonium) and rare-earth elements are similar, so the solubility of plutonium is expected to be comparably high in this formulation. In the latest experiments, this glass has dissolved greater than 10% by weight of plutonium. Now it is being optimized and further characterized for plutonium solubility, the influence of required additives such as the neutron absorber, tolerance to process variations, processability, resistance to radiation damage, and long-term chemical durability.

Ceramic Forms and Processes

Since the late 1970s, ceramic waste forms have been considered for use in immobilizing high-level waste. But no industrial experience base exists for this technology, so it is not as mature a technology as the borosilicate glass forms.

Like glass, ceramic forms must be characterized for plutonium solubility, the influence of required additives such as a neutron absorber, tolerance to process variations, processability, resistance to radiation damage, and long-term chemical durability.

The most advanced ceramic formulation to date is Synroc. ANSTO initiated development of Synroc in 1978 and completed a demonstration plant in 1987 that operated at a commercial scale of approximately 10 kilograms per hour and produced more than 6,000 kilograms of Synroc.

Fabrication processes for ceramic forms also determine how much plutonium may be incorporated into the forms. The best demonstrated process for ceramic fabrication, especially ceramic with an internal radiation barrier, is hot pressing. The process has been demonstrated full-scale with high-level-waste surrogates, but only on a laboratory scale with plutonium. At Livermore, a hot press capable of producing about 0.5-kilogram ceramic in a 7.5-centimeter-diameter bellows has been built and installed and has produced ceramic product containing about 60 grams of plutonium.

Repository Performance

An immobilization form is judged acceptable for disposal in a federal geologic repository according to a fitness-for-purpose criterion that includes regulatory, licensing, and long-term performance factors. The main long-term, post-emplacement performance considerations are criticality safety and the potential of the form to contaminate the biosphere. In the U.S., the regulatory performance period for high-level waste and spent fuel in a geologic repository has been specified as 10,000 years. (The pertinent regulations are currently under review and may change.) However, the emplaced plutonium and its uranium-235 decay product remain fissile over much longer periods (hundreds of thousands of years for plutonium and billions of years for uranium-235), over which criticality safety may need to be assured.

Scenarios for criticality events can be divided into three categories of criticality safety: safety of the essentially undisturbed emplacement waste package, safety of disrupted waste packages, and safety of disposed fissile materials released from the disposal form followed by possible transport within the repository or in the geosphere. In general, the criticality safety of the first category of scenarios can be assured with very high confidence, but assuring the safety of the latter two categories is more difficult and will depend on such factors as the fissile material content of the disposal form, canisters, and waste package; the geometry of the disrupted configuration; and the degree of degradation of the disposal form and its interactions with surrounding rock and water.

Notwithstanding the complexity of the problem, key properties of disposal forms that affect criticality safety have been identified. They are fissile loading of disposal forms, concentration of the neutron absorber, and neutron absorption properties of the immobilization matrix. Other factors are resistance of disposal form constituents to release and transport by groundwater and the rates and relative timing of releases of different components. Characteristics of elemental release from disposal forms may be very different for different disposal forms (especially glass and ceramic) and are affected by compositions of water and disposal form, solubility of the constituents, active surface areas available for reaction with water, compositional and thermal stability of disposal forms, physical and chemical homogeneity of disposal forms, and radiation effects (damage in disposal form and radiolysis in water). Researchers are particularly concerned about the susceptibility of the disposal form to cracking during fabrication and after emplacement and to the development of permeable channels within the disposal form caused by preferential dissolution of certain phases or along grain boundaries.

Lawrence Livermore and its partners are providing needed information for DOE's final immobilization technology decision, expected by September 1997. By then, they will have defined formulations for the glass and ceramic immobilization forms, characterized them for proliferation resistance and performance in the geologic repository, and developed the information needed to evaluate concepts for production processes.

Science to End Cold War

The surplus weapons plutonium disposition program is but one of several programs to help implement political agreements and maintain safeguards and security for the nation. In light of the complexity of the disposition program, both in terms of scope and required scientific expertise, declaring the Cold War over was simpler than implementing its end. At Lawrence Livermore, scientific progress is being made to contribute to that end.

—Gloria Wilt

Key Words: ceramics, deep boreholes, fissile materials, immobilization, nuclear waste repository, plutonium disposition, plutonium oxide processes, spent fuel standard, Synroc, vitrification, waste forms, weapon pits.

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Leonard Gray, the chief scientist for Lawrence Livermore's Excess Fissile Materials Disposition Program, with a prototype stainless-steel canister, which is 3 meters (10 feet) tall and 60 centimeters (24 inches) in diameter and weighs 1,680 kilograms (about 2 tons).

About the Livermore Team

Members of Livermore's Fissile Materials Disposition Program team (clockwise from lower left): MARK BRONSON holds a B.S. in metallurgical engineering and an M.S. in metallurgy from the University of Utah. In addition to being leader of the defense-related projects in the Isotope Separation and Advanced Manufacturing Program at Livermore, he leads the plutonium pyrochemistry work of the Fissile Materials Disposition Program. Particular accomplishments are development of the pit splitter for recovering excess plutonium from the cores of nuclear weapons and the hydride/oxidation process that converts plutonium to plutonium oxide prior to immobilization. He came to the Laboratory in 1988 by way of DOE's Rocky Flats facility in Colorado, where he concentrated on research and development in the field of plutonium pyrochemical technology.

BARTLEY EBBINGHAUS joined the Laboratory in 1991 after earning his doctorate in chemistry at the University of California, Berkeley. He is currently task leader for Livermore's ceramic immobilization work on DOE's Fissile Materials Disposition Program. He co-designed the formula and fabrication process for the proposed ceramic form (a variation of a material called Synroc) that is able to incorporate and immobilize excess plutonium. He has also demonstrated the successful preparation of a large plutonium-bearing ceramic pellet that meets preliminary design expectations.

GUY ARMANTROUT joined the Laboratory in 1965. He holds a doctorate in electrical engineering and physics from Purdue University. He is a project leader in the Fissile Materials Disposition Program responsible for the development and demonstration of production-scale processing systems for the immobilization of plutonium in glass and ceramic in preparation for disposal in a geologic repository.

LEONARD GRAY (Ph.D., University of South Carolina) has been a part of DOE's Fissile Materials Disposition Program since its inception in 1990, when he was asked to organize and lead an international team responsible for developing the immobilization portion of the program. After a 20-year career as a staff chemist at DOE's Savannah River Site, he joined the Laboratory in 1988 as a section leader for plutonium process development in the Special Isotope Separation Program. He is currently chief scientist for Livermore's contributions to the Fissile Materials Disposition Program.

Gamma-Ray Imaging Spectrometry

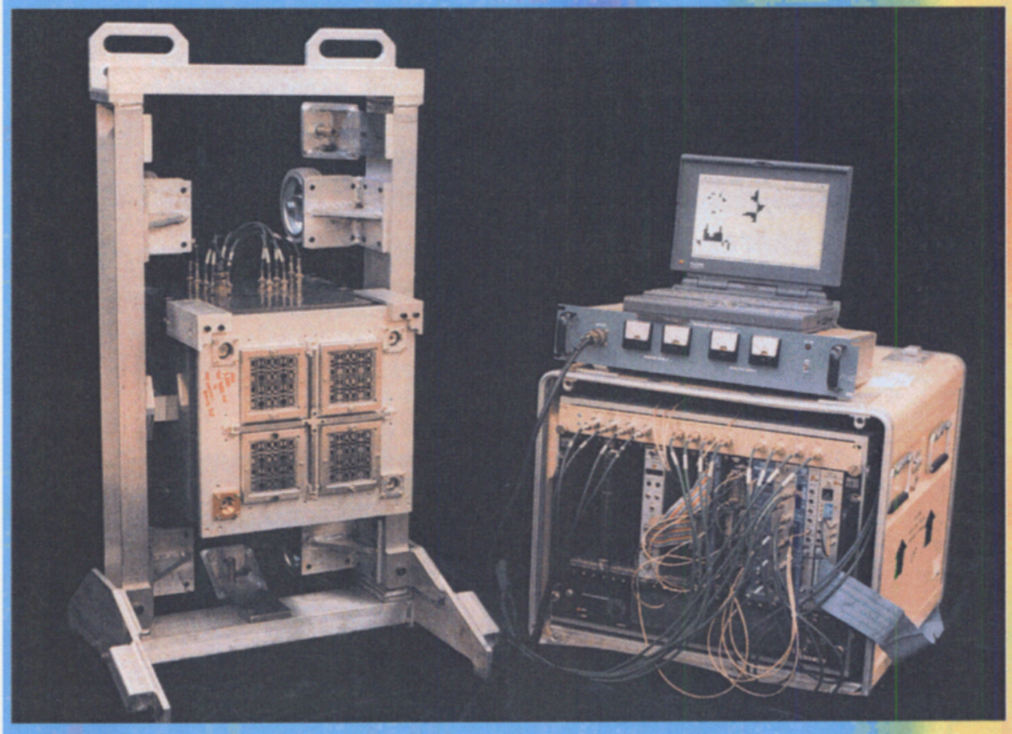


Figure 1. A Gamma-ray imaging spectrometer (GRIS) configured for work in gaseous diffusion plants. On the left, the GRIS imager head has four independent gamma-ray imagers. On the right is its data-acquisition system.

ONE of the challenges facing today's world is to keep track of the nuclear material generated during the Cold War. Some of the materials are radioactive isotopes that fuel nuclear weapons; others are used in the nuclear power industry. At Lawrence Livermore National Laboratory, we have developed an instrument that can help locate and identify these materials.

One of the characteristics of many nuclear materials, including those used in weapons, is that they emit gamma radiation. Each isotope emits a unique spectrum of gamma rays that can penetrate substantial amounts of ordinary matter without being scattered or absorbed like visible light. This radiation is imagable and can be used to indicate the presence and specific type of nuclear material.

Although nonimaging, nondirectional gamma-ray radiation detectors have long been used to monitor the presence and general location of nuclear materials, gamma rays have been poorly exploited to provide information about the precise location of the nuclear material. Recent

Laboratory scientists have developed an imaging instrument for locating and identifying nuclear materials by taking "photographs" of the gamma rays emitted by these materials. This instrument, the gamma-ray imaging spectrometer, has many potential applications as wide ranging as treaty verification, environmental cleanup investigations, gamma-ray astronomy, and nuclear medicine.

advances in position-sensitive detector technology, coupled with advances from gamma-ray astronomy, have allowed researchers to design and build a gamma-ray camera capable of taking gamma-ray "photographs" that quickly characterize radiating materials. When these images made with invisible radiation are combined with visible-light images, they clearly show the exact location of the gamma-ray emitting materials.

Looking at Gamma Rays

The gamma-ray imaging spectrometer (GRIS) we have assembled comprises four coaligned, independent imagers, each with its own detector and coded-aperture mask (Figure 1). Each detector "sees" incoming gamma rays only through its mask, which serves as the imaging optic for the gamma rays (see box, pp. 26-27). This mask is mounted on a movable mask plate in front of the detector plane; moving the plate provides different levels of zoom for the gamma-ray images.

At the back of the housing are the electronics that take the relatively weak signals from the detectors and amplify them before they are sent to the data-acquisition system, which can be located remotely. Our system currently consists of a commercial electronics module, whose data are read out by a notebook computer (Figure 1). Coaligned with the gamma-ray imagers is a video camera. Images from this provide both a visual aim point and visible light images that can be overlaid with the gamma-ray images to pinpoint the location of the radioactive material.

Applications and Results

Although the spectrometer was developed to control the special nuclear material (SNM) associated with nuclear weapons, there are a myriad of applications in other areas, including environmental cleanup, astronomy, medicine, the nuclear power industry, and any other enterprise where radioactive sources are used.

Arms Inspection

GRIS was initially designed for use in arms inspections called for by the Strategic Arms Reduction Treaty (START)—specifically, to count the number of warheads on board a missile without requiring either close access to the missile or its disassembly. Inspections would be conducted remotely, based on the premise that the gamma-ray signature from the on-board warheads, although weak, is strong enough to be detected through the top of the missile. GRIS was constructed with four detectors to decrease the time it takes to obtain a good image approximately 10 m from the source. Figure 2 shows GRIS being used to inspect a Peacekeeper missile in its silo; the missile's ten warheads in the GRIS image are easily seen in Figure 3.

Confidence through Transparency

As the U.S. and Russia strive to reduce their respective nuclear stockpiles, each must have the ability to identify and verify the location of the other's weapons components throughout the demolition process. Each

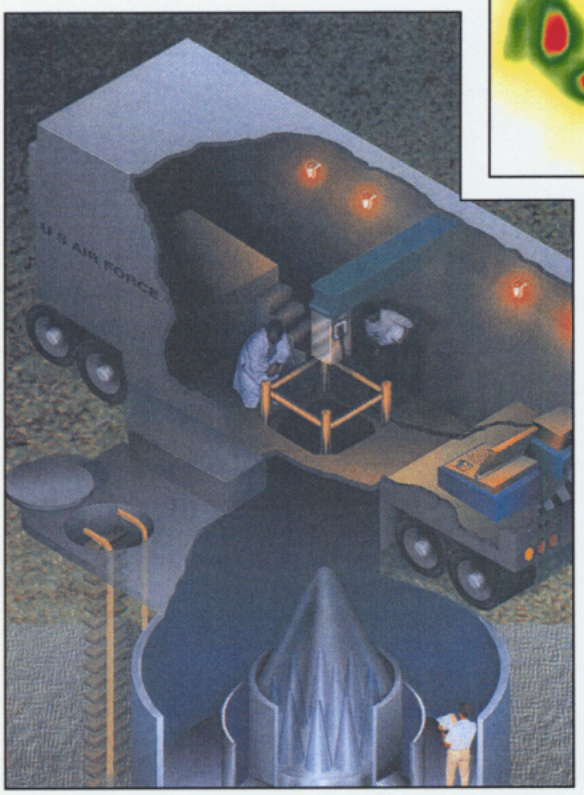


Figure 2. Rendering of the configuration used for gamma-ray imaging of a Peacekeeper missile. The GRIS imaging module is suspended above the open silo door and generates an image from the radiation given off by the warheads at the top of the missile.

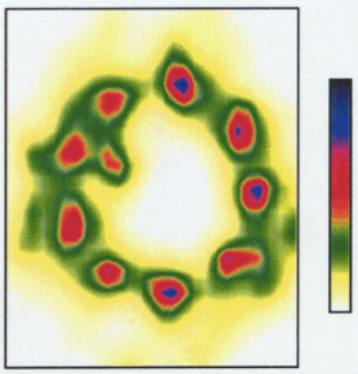


Figure 3. This enhanced gamma-ray image is from an emplaced Peacekeeper missile. The warheads are shown in a ring of nine, with the tenth inside the ring at the 10 o'clock position. The colors represent radiation intensity contours.

must have confidence that the SNM in the other's storage vessels is associated with nuclear weapons components but must be able to develop that confidence without performing an inspection that is sufficiently detailed to raise classification issues. This ability, or confidence, is called transparency.

In a recent joint U.S.–Russian demonstration at LLNL, we obtained data with a conventional, nonimaging gamma-ray detector and with GRIS. The data were collected from a radioactive source hidden inside a typical weapons component storage container. Both detectors possessed similar energy resolutions and could identify the type of material present. However, in a single measurement, the non-imaging detector could not verify the quantity of SNM present or the likelihood that the material was a weapons component. Such information could only be obtained from the nonimaging detector by scanning it across the storage vessel in small steps. Although this generated a crude image of the object that allowed identification, it also required most of a morning to complete. By comparison, the inspection with GRIS took half an hour—a time which could be easily reduced to a few minutes. The GRIS images taken from two directions 90 degrees apart (Figure 4) clearly show that a disk of plutonium and not a weapons component is in the storage container.

Related applications that take advantage of GRIS's ability to "see" behind shielding occur in nuclear waste disposal and in the characterization of nuclear weapons. Figure 5 illustrates such an application. Here, we placed a rectangular shape made from plutonium

rods inside a storage drum. To simulate shielding, we placed a depleted uranium plate about 3 mm thick outside the drum. The uranium serves as shielding, as a source of confusing radiation, and as a different radioactive isotope.

Figure 5 indicates both the energy resolution of the system and how images using data from different spectral regions can show the locations of different materials. The image obtained using only the data in the region of the spectrum shaded blue is on the left. This image represents emission from uranium and shows only the large uranium plate. On the right is the image obtained using data in the region of the spectrum shaded pink. These data are characteristic of plutonium and reveal the rectangular figure behind the uranium inside the container.

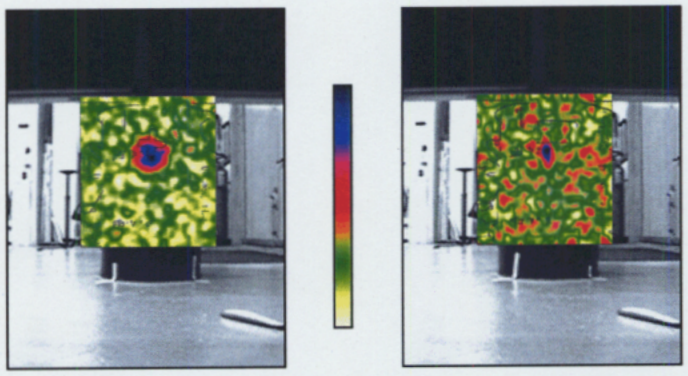


Figure 4. Overlaid on a video picture, a color gamma-ray image shows the difference between a face-on (left) and an edge-on (right) image of a plutonium disk. The images were obtained at a distance of 1.8 m and a position resolution at the source of 3.8 cm. Black represents the highest radiation intensity.

Safeguarding Weapons

When nuclear arms and their components are secured and stored, the primary concern is to verify that no material is removed from a storage area. In addition to armed guards, an inventory control system that constantly

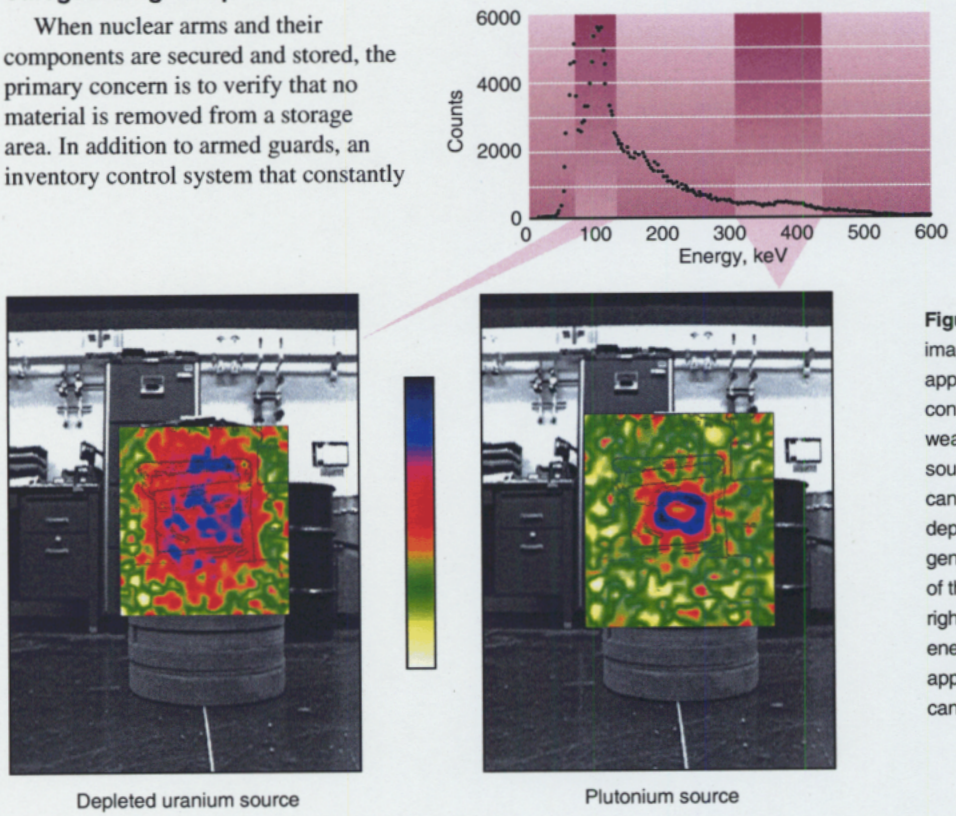


Figure 5. Demonstration of gamma-ray imaging and energy discrimination in applications for arms control transparency, contaminated waste identification, and weapons forensics. That the plutonium source is distributed inside a storage drum can be clearly seen, even through 3 mm of depleted uranium. The image at left is generated from 100-keV gamma radiation of the depleted uranium; the image on the right is generated from the plutonium energy band at about 400 keV. With the appropriate energy selection, the plutonium can be seen through the uranium.

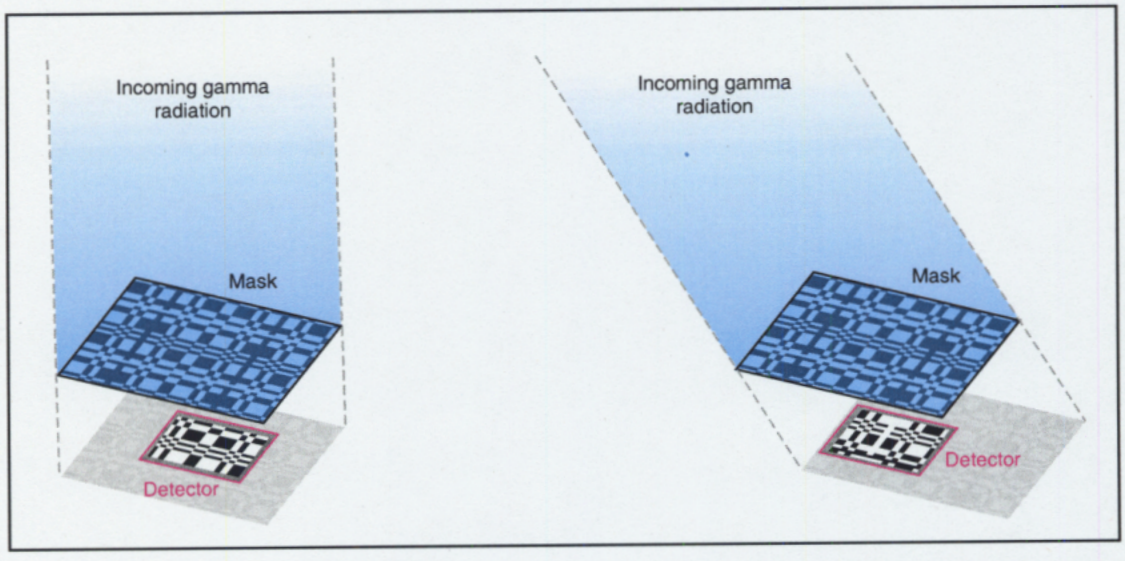
How the Gamma-Ray Imaging Detector Works

Astronomers have worked on the problem of imaging gamma rays for about 30 years. Although cosmic sources of gamma rays are extremely bright, they are also exceedingly far away, so the problem is how to image dim sources in a relatively large background. In principle, a pinhole camera could be used, but only a small fraction of the available radiation would reach the film or detector. In the late 1960s, it was recognized that one could improve the pinhole camera by punching more holes in the blocking sheet. Each hole projects its own image on the detector, and the different images overlap. If the hole pattern is known, one can mathematically recreate a faithful reproduction of the scene.

Although initial attempts showed that the technique worked, they also showed that the pattern had to be selected carefully, or false sources would appear in the image. The research on pattern effects was largely completed in the 1970s when a class of patterns called uniformly redundant arrays was created. These patterns possess a unique property: the information present in the shadow pattern from any one source in the image is not affected by the presence of gamma-ray sources in other parts of the image.

In the schematic of the imager (see the illustration below), we assume that radiation is coming from a very distant source. The light rays from this source are parallel, so a shadow of the mask is projected on the detector much the way it would be projected by the sun. Each pixel (the smallest picture element) in the image is represented by parallel gamma rays incident from one direction that project a detector-sized portion of the mask pattern onto the detector. The pattern is selected such that each projection is unique and independent of all other projections.

The image is recreated by a cross-correlation technique: the complete detector pattern is summed against each unique mask position by adding counts to the sum if the mask is open at this position and subtracting them if it is closed. Physically, counts are added if they could have come from that direction and subtracted if they could not. If no source is present, any detector-sized portion of the mask pattern has the same fraction of open



Uniformly redundant-array coded apertures produce an image by having each source pixel cast a unique mask shadow pattern on the detector. The mask is four times the area of the detector. On the left is the system response for a source in the center of the field of view. On the right, is a response for a source near the left edge of the field of view.

and closed area relative to all other portions of the mask of that same size, so the sum is zero (except for statistical fluctuations). If a source exists at the particular location being summed, then every time there is an opening there will be counts, and the sum will recreate the true flux (amount of signal per unit time) from the source.

The advantage of this technique is that half the detector area is exposed to each of the sources in the field of view. The rest is behind closed mask elements. Compare this with a pinhole camera, in which the open area is only one pixel's worth. For a point source, the signal-to-noise ratio increases as the square root of N, where N is the number of open holes. For our system, N is approximately 200, meaning a 14-times-greater signal strength and significantly reduced data-acquisition time.

Unfortunately, because all the counts in the detector are used at each image location, the more sources there are in the field of view, the less one gains from this technique. It reverts to one with the same sensitivity as a pinhole camera if the whole field of view glows at the same intensity.

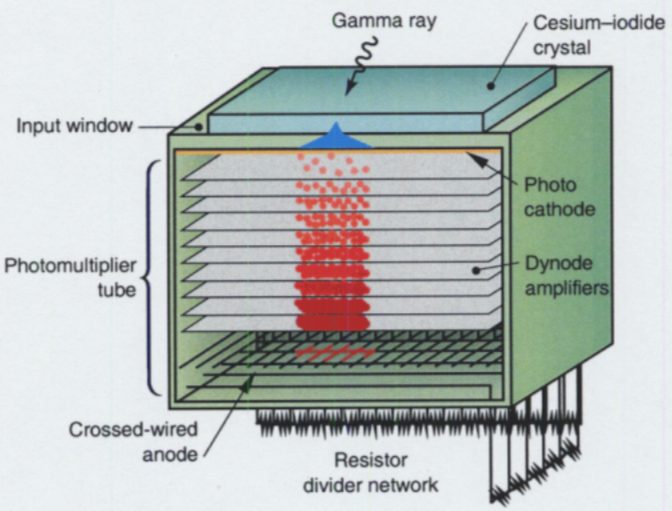
The resolution of a coded-aperture camera is just what it would be for a pinhole camera. For each pixel, the angular offset in incoming radiation is the basic hole size divided by the focal length (detector-to-mask spacing). To obtain the resolution at the source, one must multiply this angle by the distance to the source.

Position-Sensitive Detector

Converting the signal to a visual image requires a position-sensitive detector. Moreover, the position resolution must be comparable to the mask hole size; otherwise the pattern washes out. Because typical position-sensitive detectors (known as Anger cameras) for gamma rays of energies from 20 kiloelectron volts to greater than 1 megaelectron volt have position resolutions of the order of 1 cm, an imager must be quite large to have a reasonable number of pixels across the detector. An imager made with such a detector must also have a long focal length to achieve even modest position resolutions at the source

Our development of a gamma-ray detector with a position resolution of about 1 mm allowed the full exploitation of the coded-aperture technique in a compact system. In the schematic of the detector at the left, a position-sensitive photomultiplier tube is combined with a thin cesium–iodide crystal. When a gamma ray hits the crystal, it causes a brief flash of light, which is converted to an electronic signal by the photomultiplier tube. The tube is unique in that it allows the position of the light flash to be determined from its four output signals. The amount of light is proportional to the energy of the gamma ray and is also measured by the photomultiplier tube. The 4- × 5-cm active area of the detector yields about 40 pixels across its face, allowing for a mask pattern about 20 × 20 pixels (ideally, one oversamples by a factor of two.)

This schematic of the GRIS detector shows how it locates gamma radiation. A sodium-doped cesium–iodide crystal emits a flash of light when struck by a gamma ray. This light is converted to electrons and amplified by the photomultiplier tube on which the crystal is mounted. The tube uses a unique mesh dynode structure and a crossed-wire anode to determine the location of each event over the face of the tube.



monitors the radiation from each radioactive component is desirable. However, such a level of security is not always possible. Particularly in establishing an interim storage area, the costs and time required to make individual security monitors for each location can be prohibitive. However, the need for such facilities will be particularly important as U.S. and states of the former Soviet Union dismantle nuclear warheads. In this case, a GRIS-type imager can be a relatively inexpensive and very rapid way to establish inventory control.

Although we have not fielded such an application, the implementation is straightforward. The gamma-ray imager is installed so that it can "see" all sources, and a baseline image is taken. Then, the imager is set on a timer to take that image over and over again. A mathematical comparison of each successive image to the original can be used to sound an alarm should something be moved; we developed suitable algorithms to do this in the course of analyzing the Peacekeeper data. The advantages of using an imager in this case are that it can be set up very quickly, personnel need not leave the room, and visible light is not required.

Locating SNM in Process Plants

GRIS has been demonstrated at two U.S. gaseous diffusion, uranium-enrichment plants—K-25 at Oak Ridge, Tennessee, and the Portsmouth plant near Portsmouth, Ohio. The images we obtained from these plants demonstrate the utility of gamma-ray imaging in a number of complex situations.

Gaseous diffusion is used to separate the useful uranium-235 isotope from the predominant uranium-238 isotope present in natural uranium. Uranium-235 is the fissionable material used both as nuclear fuel in reactors and as weapons components. In the gaseous diffusion process, uranium metal is combined with fluorine to make uranium hexafluoride (UF_6), which is a

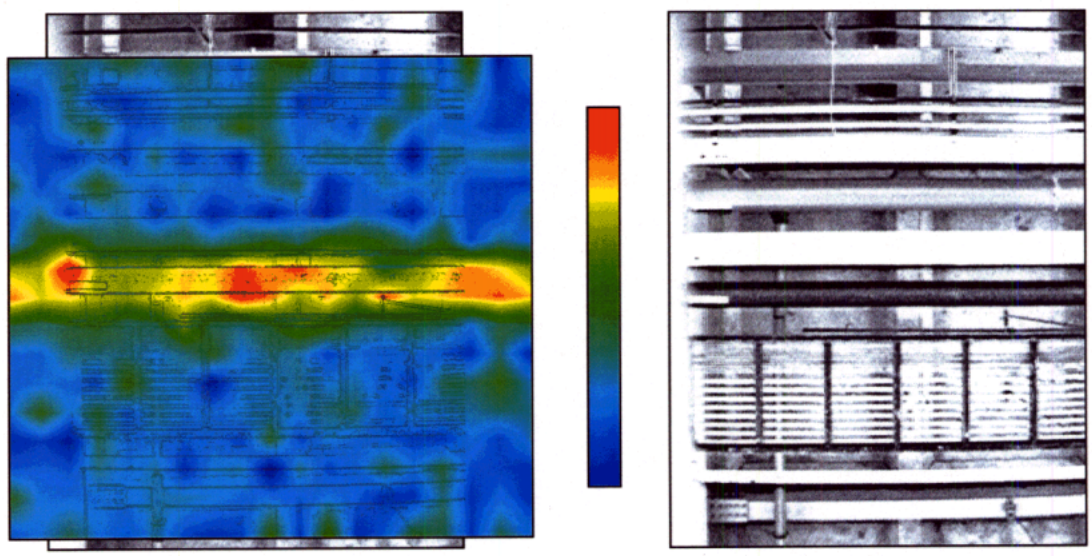


Figure 6. Video (right) and composite gamma-ray/video overlay (left) of a contaminated pipe at the K-25 gaseous diffusion plant at Oak Ridge. The gamma-ray image clearly shows which of the pipes overhead is contaminated.

gas at elevated temperatures. Separation takes advantage of the fact that the gas, composed of the lighter uranium-235 isotope, diffuses at a slightly higher rate than the gas containing heavier uranium-238. The UF_6 is enriched in heated equipment and piping contained within insulated housings.

Occasionally, because of leakage of wet air or environmental changes in the housing, solid UF_6 deposits develop. Such deposits routinely occur in an operational plant and must be located and identified. This task is not trivial. Many different pipes share the same heat shielding in the miles of pipe galleries. To enter these enclosures, workers must don protective gear to avoid radioactive contamination from possible residual leaks from more than 30 years of operation. In addition, some facilities—including those going through decontamination and decommissioning—contain highly enriched uranium, which could cause a criticality accident if a deposit of uranium-235 becomes too large.

Current characterization of the uranium deposits in these plants is performed primarily using sodium-iodide-based radiation detectors. These are carried through the plant, and readings are taken at fixed intervals to map the radiation fields. If a "hot" region is found, workers must either enter the heat-shield-enclosed area or take many measurements with a collimated version of the detectors to try to locate the deposit. Both are time-consuming, expensive, and potentially hazardous tasks. GRIS avoids these problems by generating images from outside the heat shielding that definitively locate the hot material.

Our first use of GRIS in this environment was at the idled K-25 plant. GRIS was mounted on a cart to look up some 4 m at the pipe galleries overhead that range in width from a few meters to more than 12 m across. Each gallery, enclosed in heat shielding, contains pipes ranging in size from a few centimeters to more than a meter in diameter. The building had been entirely scanned by K-25 personnel walking under and on top of the galleries using an uncollimated radiation detector; the results from this survey were used to select sites of interest for application of the GRIS imager. The first image was a pipe used to exhaust the building's many vacuum pumps. We selected this pipe because the lack of heat shielding allowed us to verify that the gamma-ray and video images identified the hot pipe (Figure 6).

A second exposure was taken of a more representative location where an isolated deposit of material was known to exist. After an initial wide-field image was taken to see the complete deposit, we moved the imager under the hot spot and zoomed in on this region. Figure 7 shows a deposit in a 1.2-m-diameter pipe, where an expansion joint exists. The deposit is probably uranium oxide, formed when a leak developed in the expansion joint.

The images from the next location, although they are nearly featureless, clearly demonstrate the power of the technique. We took GRIS to a location where we expected to find a series of radioactive pipes running the length of the area covered in the image. Two exposures were needed to cover the full width of the 12-m-wide pipe gallery. The resulting images (Figure 8) revealed only a few hot spots, not the contamination expected from the standard analysis.

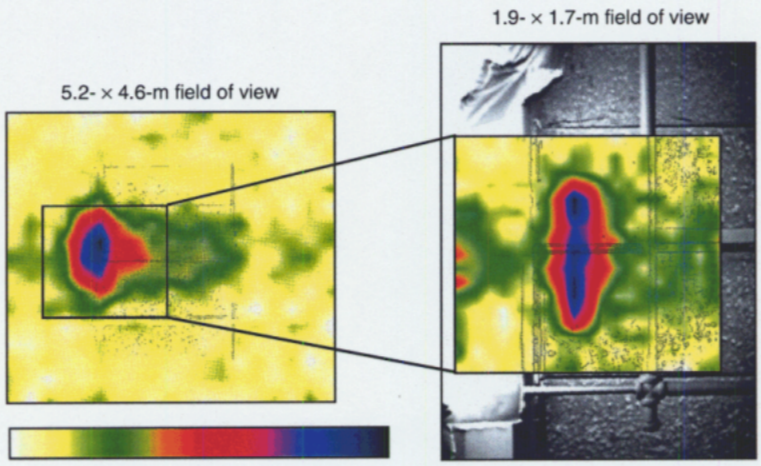


Figure 7. Overlay of gamma-ray intensity as a function of position for wide-field (left) and zoom views (right). The gamma-ray image on the right, which is overlaid on a video image, was taken after the imager was moved under the hot spot initially identified from the image on the left. The radiation is emitted by a uranium deposit inside a 1.2-m-diameter steel pipe hidden behind heat shielding.

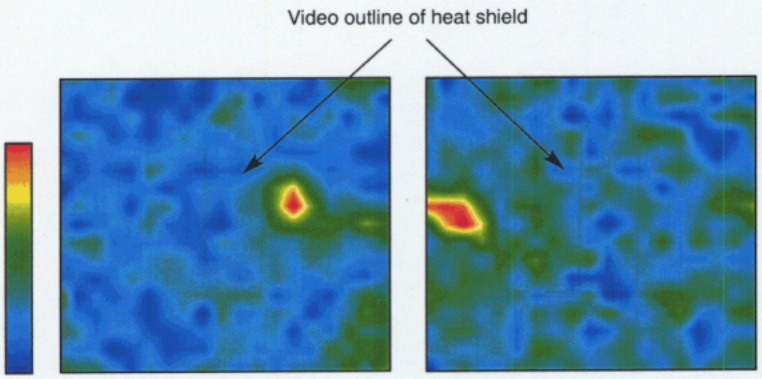


Figure 8. A powerful example of the advantages of gamma-ray imaging, this image shows little contamination within the heat shield. Instead, the image shows that the contamination is in a nearby area.

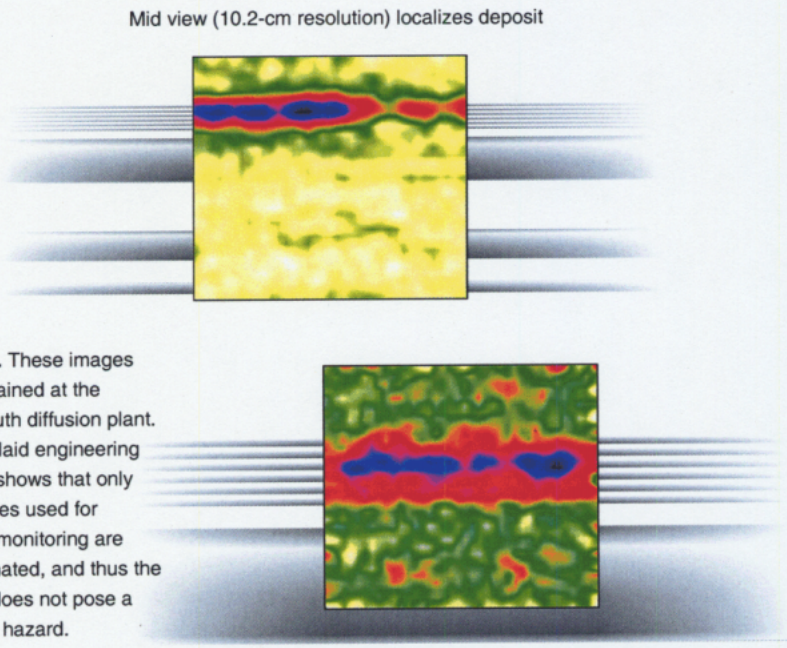


Figure 9. These images were obtained at the Portsmouth diffusion plant. The overlaid engineering drawing shows that only small pipes used for process monitoring are contaminated, and thus the deposit does not pose a criticality hazard.

Following the K-25 visit, we took GRIS to the diffusion plant at Portsmouth. There we made two measurements of note. The first was taken to determine the exact location of a known deposit of highly enriched uranium. There were concerns that a criticality accident was possible if the deposit was in the main 20- or 30-cm-diameter pipes of the gallery. One image (Figure 9) shows that this was not the case and that the deposit was in much smaller instrumentation pipes. The second image (Figure 10) shows a deposit in a diffuser cell, a large heat-shield-enshrouded area about 25 m × 6 m. The image, overlaid onto a plant blueprint, clearly shows plant personnel where the deposit is located before someone enters a cell.

In addition to its usefulness to personnel who operate and clean up these facilities, gamma-ray imaging also promises to be very useful to the International Atomic Energy Agency's safeguards programs for monitoring reactor fuel production facilities around the world. One of the major uncertainties in inspecting such plants is the nuclear material remaining in the process equipment. The ability to take images of both deposits and gas in the equipment can significantly increase the accuracy of the estimates of the quantity of material present. In addition, the settings of valves and the flow of gas through a plant can be independently verified.

Other Applications

Other GRIS applications are being considered. For example, a private company working for the nuclear power industry is studying the feasibility of using the gamma-ray/video overlay imagery to direct workers away from areas of particularly intense radiation.

In a similar application, GRIS could be used to find "lost" radioactive sources. Intense radioactive sources are sometimes used for materials characterization in construction and maintenance. If these sources are lost from their holders, they present a significant radiation hazard.

Finally, nuclear medicine could potentially benefit from application of a gamma-ray imager with capabilities similar to those of GRIS. The gamma emissions of several well-known radionuclides used in medicine fall within the range of energies GRIS exploits.

Spectrometry and the Stars

In addition to the programmatic imaging work described so far, we have collaborated with the University of California at Berkeley and at Santa Barbara to combine our unique detectors with a novel implementation of coded-aperture imaging to build the world's highest angular-resolution, gamma-ray telescope (Figure 11). Constructed with Laboratory Directed Research and Development funding, GRATIS (gamma-ray arc-minute telescope imaging spectrometer) comprises 36 individual imagers specifically tailored to work in the astronomical energy band from 20 to 200 keV. Our high-position-resolution detectors combined with a 4-m focal length allow GRATIS to achieve an unprecedented angular resolution of 2 arc-minutes (arc-min). By providing each of the 36 detectors with its own one-dimensional coded-aperture mask (Figure 12), we provide better overall performance at lower manufacturing cost than a more conventional telescope of similar size. Every one of these telescopes produces a one-dimensional

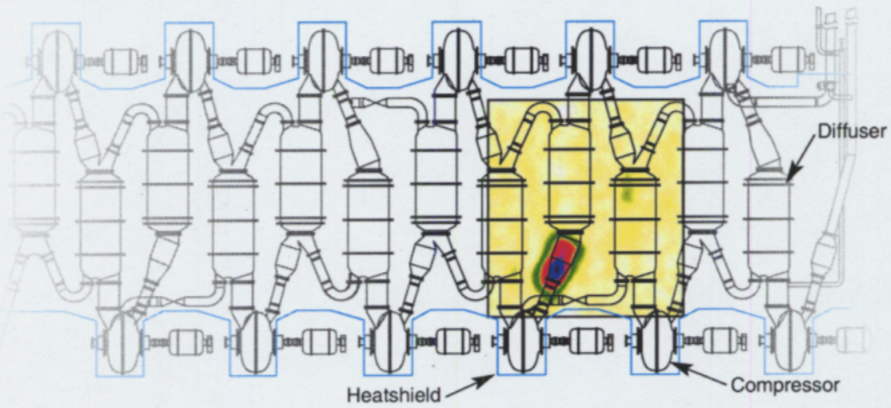


Figure 10. Overhead view of process equipment at the Portsmouth, Ohio, facility overlaid on engineering drawings of the area. The gamma-ray image clearly localizes the deposit to one length of pipe. The cylindrical diffusers are spaced about 2 m apart.

Figure 11. GRATIS is held by the launch vehicle as it is transported to the launch site at Palestine, Texas. Although significantly larger in size, the telescope is operationally very similar to the GRIS system developed for LLNL programmatic work.

picture of the sky; the images are combined mathematically to give a full two-dimensional image.

GRATIS provided a special challenge because viewing radiation from the cosmos requires that the telescope be above all but the most tenuous portions of the atmosphere. Thus, GRATIS is hung from a helium balloon, and the pointing system is operated by remote control. To keep a source in the center of the field of view requires that the pointing system be stable to 1 arc-min. To reconstruct the images properly requires that we know where the telescope is pointing to an even higher accuracy, which is obtained by using a coaligned star camera and a gyroscope system that allow us to reconstruct the pointing after the flight to approximately 20 arc-seconds.

GRATIS was first flown successfully in spring 1994 from Palestine, Texas. During its 11-hour flight, we observed three scientific targets: Cygnus X-1, Cygnus X-3, and Her X-1; we are in the process of analyzing the data. Meanwhile, GRATIS is on the ground in Alice Springs, Australia, ready for its next flight this fall, when we will observe the center of our galaxy.

Figure 12. Close-up view of the GRATIS mask plane. There are 36 individual one-dimensional masks, each rotated with respect to all the others. The resulting rotated individual images are combined mathematically to give a two-dimensional image.

Continuing Development

Our ongoing efforts in gamma-ray imaging include improvements in the detectors and in image-generation techniques. We are building a new detector that takes advantage of the rotated one-dimensional imaging used in GRATIS to extend the useful energy range of this work and to significantly lower the cost per unit area of detector. Called the Gamma-Ray Bar Imaging Telescope (Figure 13), GRABIT achieves these advances by separating the energy- and position-resolving functions of the detector.

A series of scintillator bars is mounted on a nonimaging photomultiplier tube. Most of the scintillation light from a gamma-ray event is collected by this tube, the signal from which is used to determine the energy of the gamma ray. To determine where the gamma ray hits, we pick off a small fraction of the light with a fiber-optic bundle and transmit it to an imaging device such as the photomultiplier tube used in GRIS. By observing which fiber end glows and knowing its arrangement on the imager, we can determine which bar is hit by the gamma ray.

To understand how this feature improves the system performance, note that the GRIS detectors determine an event's position by finding the center of

the light footprint at the input to the photomultiplier tube. However, as one makes the crystal thicker, the average event size will increase because the light spreads out more before it reaches the tube, thus decreasing the ability to find the flash location. By dividing the crystal into bars, we remove this problem: the position resolution is limited only by the width of the bar. The costs are lower because the unit area of nonimaging tubes is only about one-tenth that of imaging tubes. By reading out a bar with a fiber optic, we effectively increase the expensive imager area some 40 times. We are currently assembling a laboratory prototype of this detector system.

Our previous imaging work clearly demonstrates the advantage of generating images using different parts of the energy spectrum. Unfortunately, the energy resolution of the cesium iodide currently used is only about 10%, not enough to distinguish commercial (reactor-grade) plutonium from weapons-grade plutonium. Higher energy resolution makes this distinction possible because it separates the different gamma-ray energy lines of the various plutonium isotopes.

Another advantage of improved energy resolution is the ability to obtain information from a strong source that lies behind a significant thickness of other material. In such a case, the overlying material acts much like the diffuser in front of a light, scattering the radiation and blurring the image. However, unlike visible light, the scattered radiation at these higher energies is also shifted to a lower energy. By restricting the image to photons, which are in a known spectral line from the source, one can remove this type of blurring. With these advantages in mind, we plan to develop position-sensitive, solid-state detectors such as germanium- or zinc-doped cadmium telluride, both of which provide much better energy resolution.

Because it was developed for gamma-ray astronomy, the coded-aperture imaging technique as it has been applied by others assumes that the source is very far away. In the close imaging work we have described, this assumption does not hold. We have applied several techniques to compensate for this difference and are continuing to make improvements to the imaging techniques.

We are investigating the application of more advanced imaging algorithms to the coded-aperture data. These techniques rely on iterative approaches, based on Bayesian logic, that seek the best image on the basis of prior

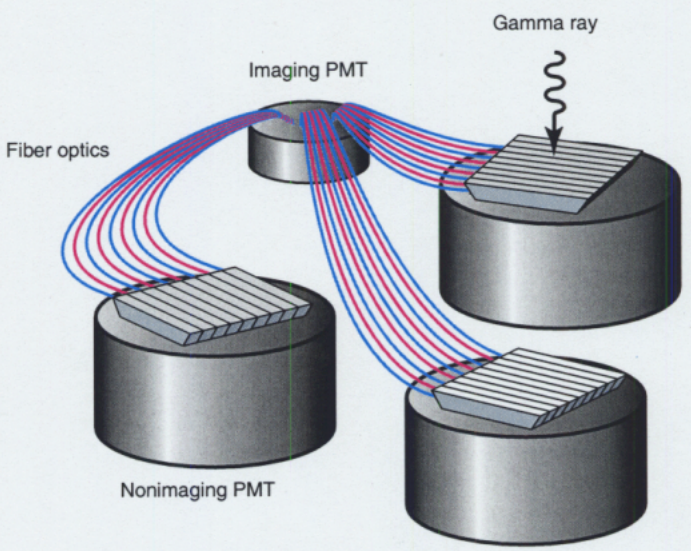


Figure 13. This schematic of the GRABIT detector shows how the position- and energy-resolving functions are separated. The light collected from the bottom of the bar arrays provides the energy information for an event. The small amount of light transported to the image tube by fiber optics allows one to determine which bar was struck.

knowledge of the source and instrument. We are already applying one such technique, known as maximum entropy, to obtain the two-dimensional image from our set of one-dimensional images in GRATIS data. This technique selects the "flattest" image (the one with the least structure) commensurate with a statistical goodness-of-fit indicator based on the known instrument properties. In this case, we assume that the scene nature supplies will not have a lot of rapid variations in counts versus position.

Key Words: gamma rays—gamma-ray arc-minute telescope imaging spectrometer (GRATIS), gamma-ray astronomy, gamma-ray bar imaging telescope (GRABIT), gamma-ray camera, gamma-ray imaging spectrometer (GRIS); special nuclear material (SNM); Strategic Arms Reduction Treaty (START).

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About the Scientist

KLAUS-PETER ZIOCK came to Lawrence Livermore National Laboratory 10 years ago as a post-doctoral scientists in V Division. Since 1988, he has been a staff scientist in V Division's Laboratory for Experimental Astrophysics. He received his Ph.D. in Physics from Stanford University in 1985 and his B.A. from the University of Virginia in Physics and Chemistry in 1978. His primary area of scientific research is low-energy gamma-ray astrophysics. He has been involved in the development of GRIS, GRABIT, GRATIS, GRB (a gamma-ray burst detector), and SXRP (an x-ray polarimeter).

His numerous publications to date (about 40) are in the area of atomic physics, including high-atomic-number systems, positronium spectroscopy, and instrumentation development for astrophysical research.

Commentary by Wayne Shotts and Lee Younker

Meeting the Monitoring Challenges of the Comprehensive Test Ban Treaty

ALTHOUGH political tensions have eased significantly between the West and the former Soviet Union, nuclear proliferation remains a grave concern worldwide. Recent events underscore this concern. In the months following the Gulf War, United Nations investigators were surprised to discover the progress Iraq had secretly made toward developing a nuclear arsenal. Just this spring, the nuclear tests by India and Pakistan raised the frightening specter of unfriendly neighbors acquiring their own nuclear missile forces and triggered urgent appeals for all nations to sign and ratify promptly the Comprehensive Test Ban Treaty (CTBT).

This ban on "any nuclear weapon test explosion or any other nuclear explosion"* is the latest step in a decades-long quest to halt nuclear proliferation. The treaty calls for an international system of several hundred monitoring stations transmitting data continuously to an international data center in Vienna, which in turn distributes the data and summary reports to national data centers, including the U.S. National Data Center in Florida.

As the article beginning on p. 36 points out, the treaty presents an unprecedented monitoring challenge: namely, detecting low-yield, clandestine nuclear tests among thousands of seismically similar events, such as small earthquakes and routine mining explosions, that will be reported daily by the monitoring stations arrayed around the globe.

The Department of Energy is drawing on the expertise and technical strengths of its national laboratories to devise tools and techniques for monitoring this most restrictive of all test bans. For its part, Livermore is home to expertise in nuclear-test-related seismology, geology, engineering, chemistry, instrumentation, and computer science. During the nation's earlier nuclear testing program, Livermore seismologists, geologists, and engineers, many of them now a part of the Earth and Environmental Sciences Directorate, played a critical role in ensuring the containment of the underground tests at the Nevada Test Site. In addition, our seismologists have a long history of treaty monitoring research and, along with other Livermore experts, have provided technical support and advice to U.S. policymakers and treaty negotiators for all of the treaties limiting underground nuclear testing.

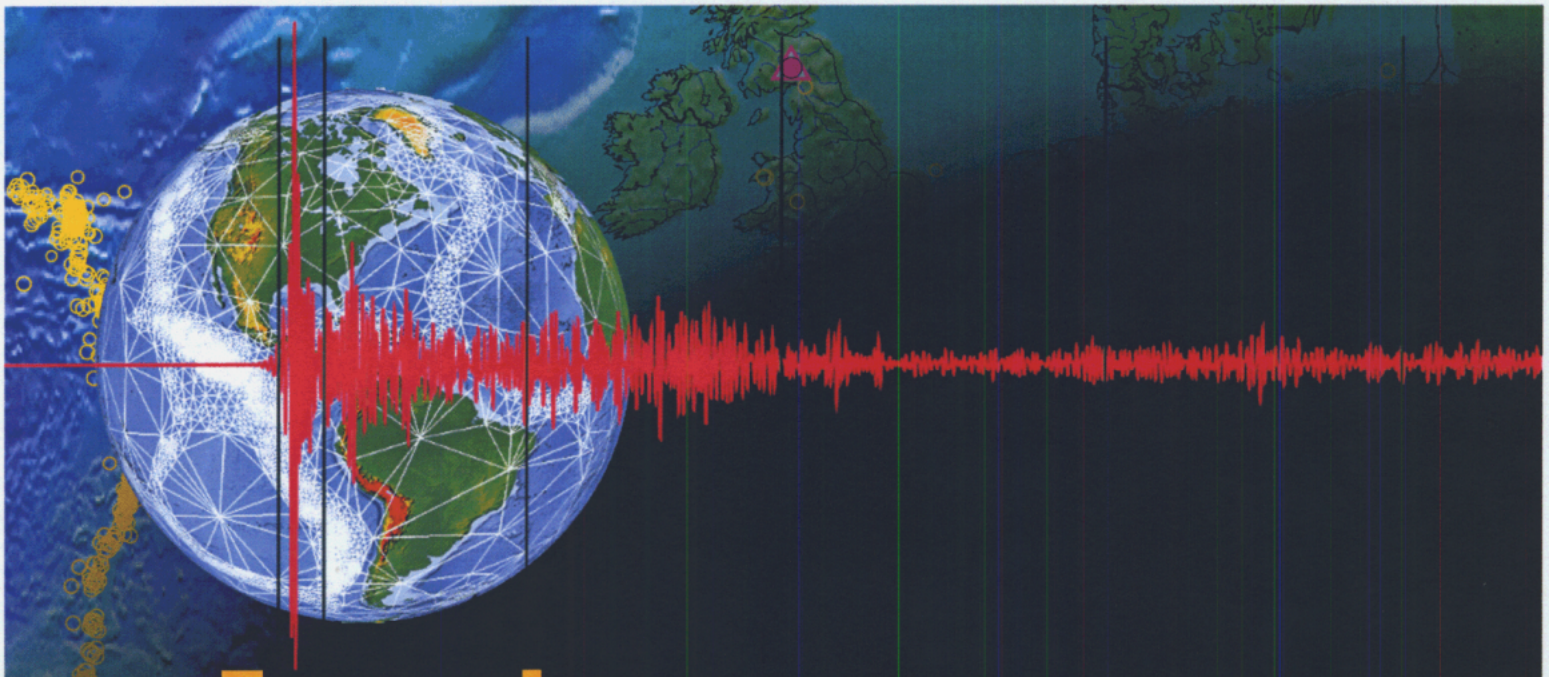
During CTBT negotiations in Geneva a few years ago, Livermore made major contributions to the selection of international monitoring station sites, the definition of on-site inspection procedures, and even the adoption of national monitoring concepts undergirding the treaty. For the past few years, Livermore researchers have been working on several projects to help the U.S. National Data Center prepare for a CTBT. One vital effort focuses on determining how the regional geology in key parts of the world, such as the Middle East, will affect seismic signals as they travel underground from explosions, earthquakes, and other sources to the international monitoring stations. As the article describes, fulfilling this task has taken Livermore people to remote corners of the world and even teamed them with colleagues in Russia to calibrate seismic wave propagation in areas of the former Soviet Union.

The research team's work supports Livermore's Nonproliferation, Arms Control, and International Security Directorate—in particular, its Proliferation Prevention and Arms Control Program. Among this program's responsibilities are conducting analyses in support of DOE nuclear arms control policies and guiding the development of treaty verification technologies. Indeed, the directorate was created in part to use Livermore's core strengths in nuclear science and advanced sensors and instrumentation to help this nation prevent the spread of nuclear weapons and supporting technology.

Livermore and the other DOE national security laboratories have an essential role to play in providing the analyses and technologies needed to monitor compliance with arms control treaties. This role, as never before, demands technological inventiveness from experts representing a host of mutually supporting disciplines, with the overriding goal of enhancing national and global security.

*From the text of the CTBT, which can be viewed at *http://www.acda.gov/treaties/ctbt.htm.*

- Wayne Shotts is Associate Director, Nonproliferation, Arms Control, and International Security.
- Lee Younker is acting Associate Director, Earth and Environmental Sciences.



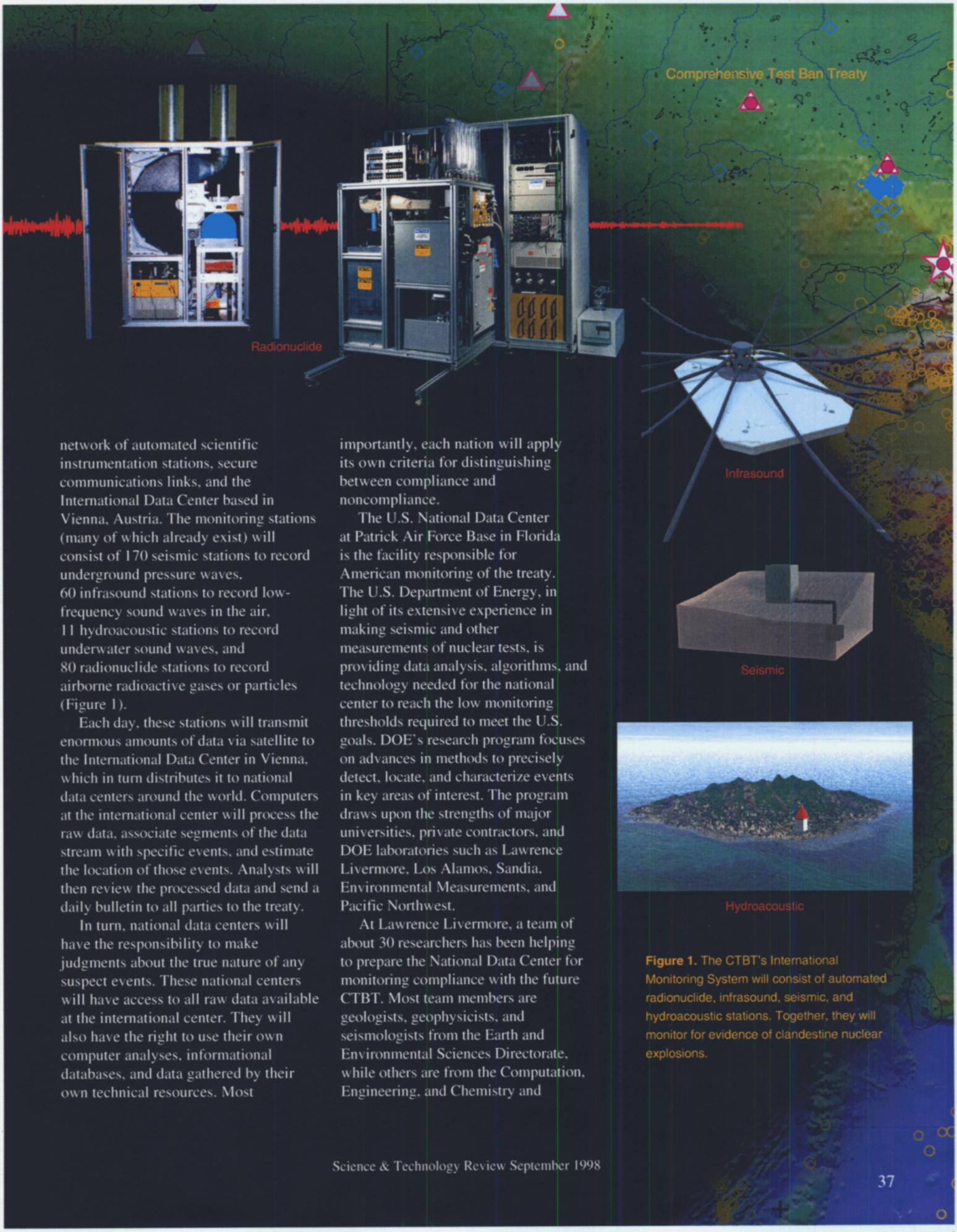
Forensic Seismology Supports the Comprehensive Test Ban Treaty

Some 53 years after the first nuclear explosion, a team of Livermore researchers is helping the nation prepare for the Comprehensive Test Ban Treaty by developing methods to detect clandestine nuclear tests.

THE nearly worldwide condemnation of India's and Pakistan's unexpected nuclear tests in May was a telling indicator of the determination of nearly all nations to put an end to nuclear testing. That determination is embodied in the Comprehensive Test Ban Treaty (CTBT), signed in 1996 following a half-century of passionate discussions, various proposals, and international research to ensure that attempts to evade the treaty would be detected.

The CTBT forbids all nuclear tests, including those intended for peaceful purposes, and creates an international monitoring network to search for evidence of clandestine nuclear explosions. The agreement—signed by President Clinton but still to be ratified by the U.S. Senate—is of profound interest to dozens of scientists at Lawrence Livermore. They have worked over the past several years to support American diplomats in achieving this international agreement backed by sound monitoring and verification measures. Lawrence Livermore scientists have developed monitoring technologies in support of nuclear treaties and have outstanding credentials in providing technological support to treaty negotiations and verification. (See the box on p. 39.)

The CTBT's International Monitoring System will consist of a



network of automated scientific instrumentation stations, secure communications links, and the International Data Center based in Vienna, Austria. The monitoring stations (many of which already exist) will consist of 170 seismic stations to record underground pressure waves, 60 infrasound stations to record low-frequency sound waves in the air, 11 hydroacoustic stations to record underwater sound waves, and 80 radionuclide stations to record airborne radioactive gases or particles (Figure 1).

Each day, these stations will transmit enormous amounts of data via satellite to the International Data Center in Vienna, which in turn distributes it to national data centers around the world. Computers at the international center will process the raw data, associate segments of the data stream with specific events, and estimate the location of those events. Analysts will then review the processed data and send a daily bulletin to all parties to the treaty.

In turn, national data centers will have the responsibility to make judgments about the true nature of any suspect events. These national centers will have access to all raw data available at the international center. They will also have the right to use their own computer analyses, informational databases, and data gathered by their own technical resources. Most importantly, each nation will apply its own criteria for distinguishing between compliance and noncompliance.

The U.S. National Data Center at Patrick Air Force Base in Florida is the facility responsible for American monitoring of the treaty. The U.S. Department of Energy, in light of its extensive experience in making seismic and other measurements of nuclear tests, is providing data analysis, algorithms, and technology needed for the national center to reach the low monitoring thresholds required to meet the U.S. goals. DOE's research program focuses on advances in methods to precisely detect, locate, and characterize events in key areas of interest. The program draws upon the strengths of major universities, private contractors, and DOE laboratories such as Lawrence Livermore, Los Alamos, Sandia, Environmental Measurements, and Pacific Northwest.

At Lawrence Livermore, a team of about 30 researchers has been helping to prepare the National Data Center for monitoring compliance with the future CTBT. Most team members are geologists, geophysicists, and seismologists from the Earth and Environmental Sciences Directorate, while others are from the Computation, Engineering, and Chemistry and

Figure 1. The CTBT's International Monitoring System will consist of automated radionuclide, infrasound, seismic, and hydroacoustic stations. Together, they will monitor for evidence of clandestine nuclear explosions.

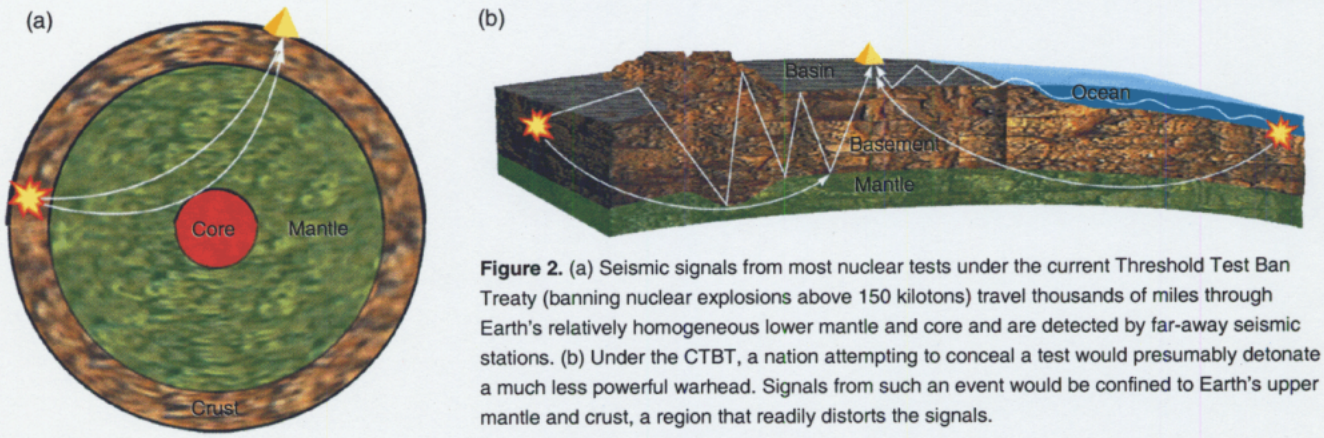


Figure 2. (a) Seismic signals from most nuclear tests under the current Threshold Test Ban Treaty (banning nuclear explosions above 150 kilotons) travel thousands of miles through Earth's relatively homogeneous lower mantle and core and are detected by far-away seismic stations. (b) Under the CTBT, a nation attempting to conceal a test would presumably detonate a much less powerful warhead. Signals from such an event would be confined to Earth's upper mantle and crust, a region that readily distorts the signals.

Materials Science directorates. The team's work supports the Laboratory's Nonproliferation, Arms Control, and International Security Directorate, which helps prevent the proliferation of weapons of mass destruction and assists in U.S. arms control matters.

For the CTBT, Livermore is carrying out field experiments, at sites ranging from the deserts of Jordan to the former Soviet nuclear test site in Kazakhstan, to document how regional geology affects the transmission of seismic signals. At the same time, Livermore specialists are developing powerful computer algorithms that calculate the degree to which measurements collected by seismic and hydroacoustic stations are altered by regional geology and how they compare with previous data from, say, regional earthquakes and mining operations (activities that can mimic small nuclear explosions). Finally, Livermore experts provide technical advice and expertise to U.S. negotiators and developed methods for international teams to use for on-site inspections. (See the box on p. 42.)

"Our goal is to achieve a very high level of confidence in the nation's ability to detect any clandestine nuclear explosion," says Livermore program leader Jay Zucca, a seismologist. Zucca notes that while DOE is the sponsor of this work, the primary user for the Livermore research program is the U.S. National Data Center. Livermore is also working closely with representatives of the Provisional Technical Secretariat (the international organization created by the treaty for its implementation) in Vienna in establishing the International Monitoring System and data center.

Meeting Monitoring Challenges

Zucca points out that under the current Threshold Test Ban Treaty (banning explosions exceeding 150 kilotons), determining accurate explosive yield is the critical issue. Most nuclear tests near the threshold treaty's limit generate seismic magnitudes of about 6 or greater on the Richter scale. Seismic signals from these tests travel thousands of miles through Earth's relatively homogeneous core and mantle and are readily picked up by far-away seismic stations for relatively straightforward characterization (Figure 2a).

Under the CTBT, however, the critical issues will be to determine that a nuclear explosion—no matter its size—took place and to pinpoint its location accurately. A nation attempting to conceal a test could attempt to minimize the seismic signals. Such signals from a small nuclear test could be well below magnitude 4, with resulting measurable signals traveling 1,000 miles or less. What's more, the signals would likely be confined to Earth's upper mantle and crust, an extremely heterogeneous environment that distorts, and even blocks, parts of the signals (Figure 2b).

Accurately locating and characterizing signals at these so-called regional distances pose a significant challenge, says seismologist Bill Walter. "It's a much harder job because we can't use global models of Earth. We have to calibrate region by region, seismic station by seismic station." Successfully meeting the regional distance challenge, says seismologist Marv Denny, has been the most difficult aspect of the Livermore effort over the past several years.

Denny says that complicating the task is the huge number of events that, at first cut, can resemble a small nuclear detonation. Stations will be recording a constant stream of background noise that includes earthquakes, lightning, meteors, sonic booms, navy armament testing, mining explosions, construction activities and other industrial operations, nuclear reactor operations and accidents, natural radioactivity, and even strong wind and ocean waves.

"As we consider the possibility of smaller and smaller clandestine tests, the

The Road to a Comprehensive Test Ban Treaty

Awed by the destructive power of nuclear weapons, scientists and others began discussing banning further weapons tests shortly after Trinity, the first test of a nuclear explosive in 1945. Since then, a succession of treaties has slowly narrowed the lawful testing environments. For example, the Limited Test Ban Treaty, ratified in 1963, banned nuclear explosions in the air, oceans, and space, while the Threshold Test Ban Treaty, ratified in 1988, limited underground nuclear weapon tests to 150 kilotons.

The Comprehensive Test Ban Treaty was signed by President Clinton and other heads of state on September 24, 1996, at the United Nations, following two years of international negotiations. In signing the treaty, President Clinton used the same pen President John F. Kennedy used to sign the Limited Test Ban Treaty. Following the signing ceremony, the President told the United Nations General Assembly that the treaty "points us toward a century in which the roles and risks of nuclear weapons can be even further reduced—and eventually eliminated."

As of mid-1998, the treaty has been signed by 149 nations and ratified by 13 nations. The treaty will not enter into force until ratified by the 44 nations named in the treaty that possess nuclear reactors. The U.S. has signed but not ratified the treaty; three other named nations—India, Pakistan, and North Korea—have neither signed nor ratified the treaty.

Under the treaty, each nation undertakes "not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control." Each party also undertakes "to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapons test explosion or any other nuclear explosion."

Other articles of the treaty describe the international monitoring system, on-site inspections, confidence-building measures, organization of the treaty's executive council and the technical secretariat, and measures to redress violations. (The main text of the treaty may be viewed at *http://www.acda.gov/treaties/ctbt.htm.*)

An international organization, the Preparatory Commission in Vienna, Austria, was established in November 1996 to create the international monitoring and verification regime.

number of background events, both natural and human made, becomes immense," says Walter. For example, more than 200,000 earthquakes similar in seismic magnitude to a small nuclear explosion occur in the world every year. Many of these background events can be disregarded because of their depth or similarity to other events known to be nonnuclear. However, many will not be identified so readily. As a result, the National Data Center will require a set of tools, largely data-processing software, modeling capability, and reference databases, to perform what Walter terms "forensic seismology" to separate a weak potential nuclear test from background noise.

One essential tool will be a comprehensive database that includes seismic patterns and the location of mines and seismically active regions. This database must also include information on how Earth's crust and mantle affect the travel time and amplitude of seismic signals as they make their way to international stations. "We want to be sure that data relayed by individual stations are interpreted in light of their regional settings so that the location and nature of an event are properly determined," says Zucca.

Building the Knowledge Base

The DOE is assembling such a database, called the Knowledge Base, to manage, store, and retrieve vital information about major areas of the world. "A key Livermore product for the National Data Center is our contribution to the Knowledge Base," says Zucca. While the Knowledge Base includes information from all four sensor technologies, it is dominated by hydroacoustic and seismic data, considered the most essential for interpreting events in their regional context.

The Livermore team has been assigned by DOE to focus largely on the Middle East and North Africa (called MENA) and the western part of the former Soviet Union, which includes the former Soviet test site at Novaya Zemlya, near the Arctic Sea (Figure 3). The work has entailed collecting and organizing large quantities of geological, geophysical, seismological, and human-activities data within these areas. The task is complicated by the geological diversity of MENA and by the lack of "ground truth," that is, seismic data from well-documented earthquakes, mine explosions, or explosions carried out for seismic calibration purposes.

Obtaining needed ground truth has prompted several avenues of research. Geologist Jerry Sweeney, for example, is researching published literature for reports of earthquake aftershock studies from Iran, Algeria, and Armenia. Other researchers have deployed temporary stations in areas awaiting the construction of permanent international stations to record background seismic activity so that they can determine how the regional geology affects the seismic readings. Last April, engineer and seismologist Dave Harris traveled to Jordan to set up two temporary seismic stations in cooperation

(a)

(b)

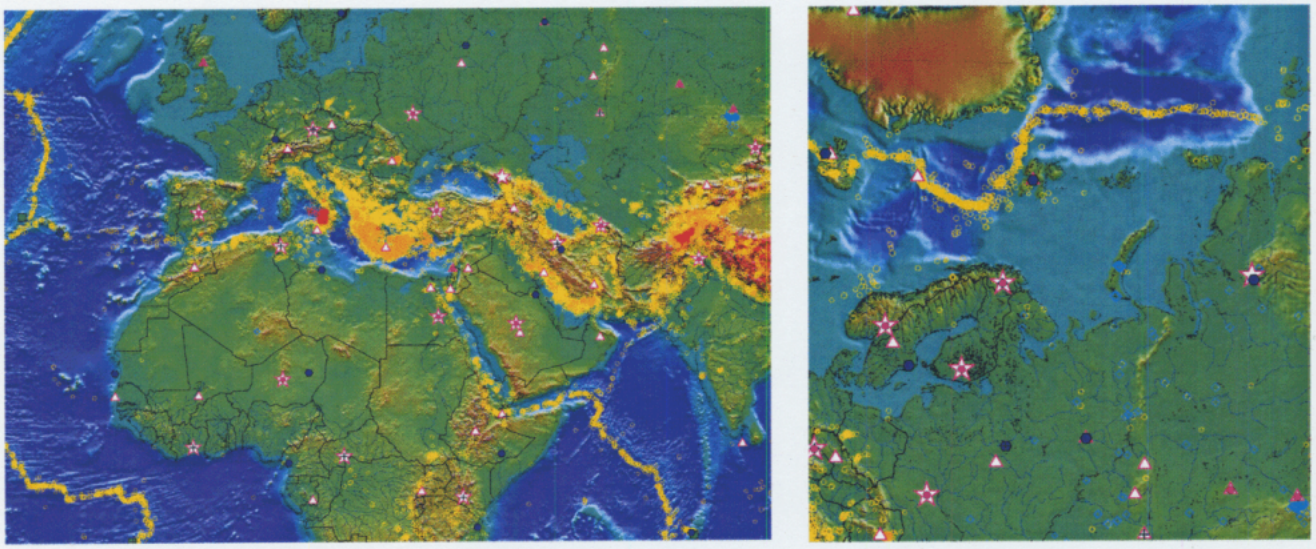


Figure 3. Livermore researchers are focusing on (a) the Middle East and North Africa and (b) the western part of the former Soviet Union, which includes the former Soviet nuclear test site at Novaya Zemlya. The locations of seismic, hydroacoustic, infrasound, and radionuclide monitoring stations for the International Monitoring System (IMS) are shown for both areas. The historic seismic record is plotted using a scale determined by the depth of the seismic signal. Past nuclear explosions (many of them for peaceful purposes) are denoted by blue diamonds. (Maps created by Livermore scientist Bill Walter.)

with the Jordanian Natural Resources Authority to record the seismic signatures of earthquake activity and nearby phosphate mining operations (Figure 4). "These extra stations provide additional constraint on the locations of earthquakes in the region and provide us with higher quality ground truth," explains Harris.

Aiding the MENA effort is an ongoing Livermore study of earthquakes and underground explosions around the Nevada Test Site. Livermore researchers are comparing seismograms of underground nuclear tests conducted in 1992 (the last year of American nuclear testing) with several moderate local earthquakes in the same year. They also participated in a DOE test at the site in 1993 (called the Non-Proliferation Experiment) involving a kiloton of chemical explosive. The test revealed that seismic signals from an underground chemical blast closely mimic the signals that would be expected from an underground nuclear test.

Zucca notes that potential treaty violators might be tempted to detonate a nuclear device in the center of a large underground cavity, a technique called decoupling. The seismic signal from such a test is reduced by a factor of up to 70 through a muffling effect that reduces the amplitude of the signal. A 1-kiloton nuclear explosion, for example, would produce a magnitude in the range of approximately 2.5 to 3 on the Richter scale when tested in a large underground cavity. Seismic signals of the lower magnitude are produced frequently in a large number of mine explosions worldwide, and many thousands of earthquakes are in this range.

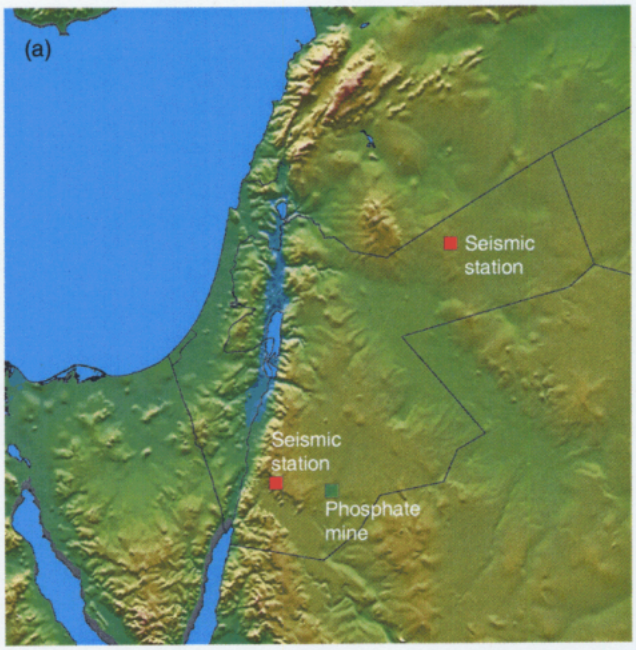


Figure 4. Livermore and Jordanian researchers recently established two temporary seismic stations in Jordan to record the seismic signatures of background earthquake activity and of explosions from phosphate mining activities from operations at the Eshidiyah phosphate mine. (a) Map of the area showing the location of the phosphate mine and seismic stations. (b) Outside view of the seismic station nearest the mine. (c) Inside view of the seismic station.

Livermore scientists have investigated the signal effects possible with blasts conducted in cavities formed from different rock types. Researchers have also attempted to gain a more complete understanding of the seismic signals caused by routine mining operations. They have joined with colleagues from the U.S. Geological Survey and Russian scientists to calibrate seismic wave propagation in regions of the former Soviet Union. Livermore scientists have also monitored different types of seismic signals from operations in mines located in Wyoming, Colorado, and Nevada.

Determining Underwater Events

While seismic network research is progressing along many fronts, several Livermore specialists have devoted their energies to advancing hydroacoustic monitoring technology. They have combined fundamental research on detecting the propagation of underwater sound waves with contributions to the Knowledge Base's storehouse of underwater signals from earthquakes, volcanoes, shipping activity, and chemical explosions from military testing. "A lot of background underwater events have to be taken into account," says seismologist Phil Harben, although he notes that they are not as pervasive as land activities such as mining.

Aiding Livermore's understanding of ocean signals is an automated data-acquisition facility on San Nicolas Island off southern California. Data from this station permit researchers to check computer models and conduct research on the sensitivities of island seismic stations and offshore hydrophones to water-borne signals.

The database of nuclear explosions at sea is limited to a few tests carried out years ago by the agencies preceding the DOE. Because data are so limited, Livermore scientists have developed a calculational capability to predict the

effects of underwater nuclear explosions. They used this capability to provide diplomats with options for hydroacoustic networks. They also provided analyses showing the economic advantages of fixed hydroacoustic stations (connected by cable to recording sites on land) over unmoored, floating buoys. On the basis of this work, a network of six hydrophones and five island seismometers was chosen as the international system to detect and locate underwater explosions and, in some cases, explosions in the low atmosphere.

The network takes advantage of the fact that underwater explosions generate acoustic waves (in the frequency range of 1 to 100 hertz) that can travel completely across an ocean basin—in some cases, more than

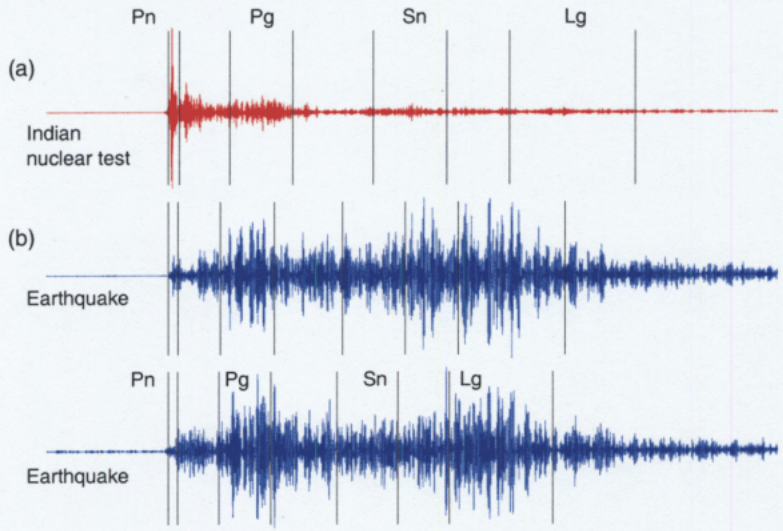


Figure 5. An international monitoring station in Pakistan detected the Indian nuclear test of May 11, 1998, about 740 kilometers away. (a) Analysis of the seismogram showed a P-wave-to-S-wave ratio strongly indicative of an explosion and not (b) nearby earthquakes.

When Monitoring Stations Aren't Enough

Under the terms of the Comprehensive Test Ban Treaty, a nation suspecting another of conducting a nuclear test may request that the treaty's 51-member Executive Council conduct an on-site inspection to determine the nature of the suspect event. The requesting nation may introduce evidence acquired on its own to strengthen its case to the organization. On-site inspections must be approved within 96 hours of receiving an inspection request because of the need to observe short-lived nuclear phenomena that are produced by a nuclear test.

Over the past decade, Lawrence Livermore experts have led the U.S. development of on-site inspection technologies and procedures; many of these procedures were eventually incorporated into the text of the treaty. Livermore seismologist Jay Zucca serves as the U.S. point of contact for the On-Site Inspection Experts Group that meets regularly in Vienna.

Zucca explains that a clandestine explosion may not necessarily form a telltale crater. In such a case, an inspection team will search for other evidence. For example, the team may deploy portable seismic equipment to detect very small aftershocks, collect samples of soil gases and water to look for radioactive materials, or search for an underground explosion cavity or rubble.

Livermore researchers have shown that low-frequency aftershocks associated with nuclear explosions may also be caused by mining operations. They compared aftershocks from the 1993 Non-Proliferation Experiment at the Nevada Test Site (in which 1 kiloton of chemical explosive was fired in an underground cavity) with those from routine operations at the Henderson Mine in Colorado. Although the events from both sources are similar, there are subtle differences in the aftershock signals. They were interested in the Henderson Mine because the caving operation is similar to the chimney formation following an underground nuclear event.

Also as part of the Non-Proliferation Experiment, Livermore experts found that very small amounts of rare radioactive gases such as xenon-133 and argon-37 generated in underground nuclear detonations can migrate toward the surface along natural fault lines and earth fissures in a time frame consistent with an on-site inspection. The technology used in these tests can be an extremely sensitive way to detect nearby underground nuclear explosions that do not fracture the surface. (See January/February 1997 *S&TR*, pp. 24–26.)

10,000 miles. The acoustic waves travel along the SOFAR (sound fixing and ranging) channel, described by Harben as "a wave guide for ocean acoustic energy that depends on temperature, density, and depth." However, waves traveling in this channel can be blocked or weakened by land masses and regions of shallow or cold water. Livermore modeling of the properties of this channel during CTBT negotiations was important in determining the global distribution of hydroacoustic stations.

Refining Algorithms

A major effort of the National Data Center will be the automated analysis of data obtained from the international center, supplemented by data provided by other U.S. resources. Final reviews will be provided by analysts working with Knowledge Base data such as reference seismograms from historic nuclear events conducted in the area of a suspect event. Key to the automated process will be several algorithms for determining the location and nature of an event. Livermore experts are using data gathered for the Knowledge Base—for example, underground signal travel times to each international station—to refine the algorithms.

As part of their algorithm work, an interlaboratory team headed by Livermore seismologist Craig Schultz made a fundamental advance in the field of kriging, a geostatistical estimating process. The advance enables the team to develop estimates of the level of confidence in the regional seismic properties derived from a few geographically isolated observations. Zucca describes the work as one of the key breakthroughs for the functioning of the Knowledge Base. It is likely, he says, that the approach taken by Schultz's team for the algorithms will be adopted by seismologists everywhere for their own applications.

Key algorithms provide discriminants, characteristic features of a waveform (peak-to-peak distance, height, width, or some ratio). A particularly useful discriminant, for example, is the ratio of P-wave amplitude to S-wave amplitude. The P (or primary) wave is a compressional wave that is the first to arrive at a station. The S wave or shear wave has a slower propagation speed and arrives behind the P wave. The seismogram from the Indian nuclear test of May 11, 1998, as recorded by an international monitoring system station in Pakistan about 740 kilometers away, showed a P-to-S ratio strongly characteristic of an explosion and not an earthquake (Figure 5).

Zucca points out that the Indian test successfully demonstrated the capability of the international network. Based on Livermore's work at other sites and current examination of events in this area, he is confident a potential nuclear explosion in key areas of interest can be detected and identified down to much smaller magnitudes. In other words, says Zucca, the world will soon have strong international monitoring and analysis capabilities to help determine international compliance with the Comprehensive Test Ban Treaty.

—Arnie Heller

Key Words: Comprehensive Test Ban Treaty (CTBT), discriminants, International Data Center, Knowledge Base, MENA (Middle East and North Africa) region, National Data Center, Nevada Test Site, SOFAR (sound fixing and ranging) channel, Threshold Test Ban Treaty (TTBT).

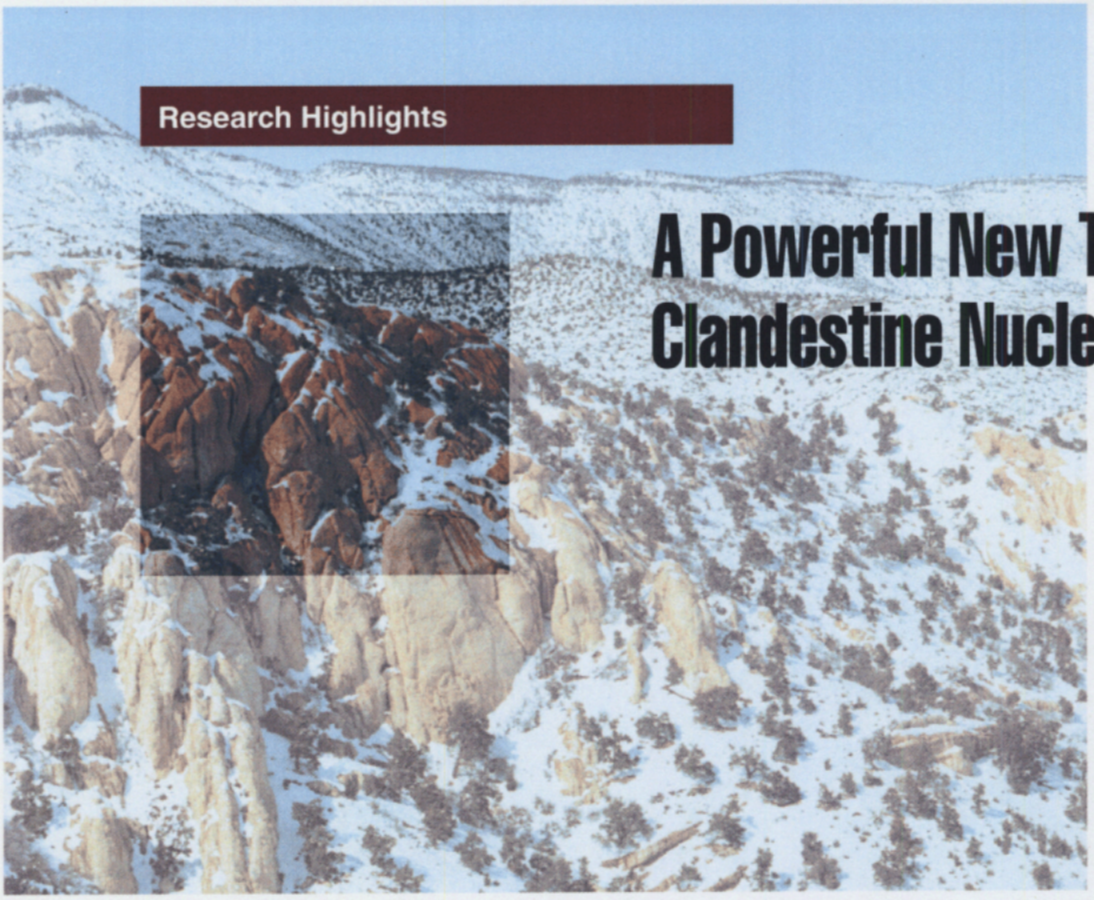
Editor's Note: On p. 36, the image of the globe is courtesy of Sandia National Laboratories, the image of the radionuclide monitoring devices was provided by Pacific Northwest National Laboratories, and the image of the infrasound monitor was created at Los Alamos National Laboratory.

For more information contact Jay Zucca (925) 422-4895 (zucca2@llnl.gov). Information on DOE's overall CTBT program may be found at www.ctbt.rnd.doe.gov.

About the Scientist

JOHN J. (JAY) ZUCCA, leader of Livermore's Comprehensive Test Ban Treaty Program, joined the Laboratory in 1984. He has worked primarily for the Laboratory's Treaty Verification Program, concentrating on seismic instrumentation development, on-site inspection, and regional seismology. He was a member of the U.S. delegation to the Nuclear Testing Talks (Threshold Test Ban Treaty) and a member of the U.S. delegation to the Conference on Disarmament for the Comprehensive Test Ban Treaty. He is currently a member of the U.S delegation to the Preparatory Commission for the CTBT. Zucca received his B.S. from the University of California at Berkeley and his Ph.D. from Stanford University. He completed postdoctoral positions at the U.S. Geological Survey in Menlo Park and the University of Karlsruhe in Germany.

A Powerful New Tool to Detect Clandestine Nuclear Tests



Experiments with the Laboratory's new method of detecting clandestine nuclear tests were conducted on the rocky Rainier Mesa at the Nevada Test Site during periods of low atmospheric pressure, mainly at the beginning of storms, so that tracer gases could rise toward the surface through natural faults and fractures.

WHEN President Clinton and other world leaders signed the landmark Comprehensive Nuclear Test Ban Treaty last September, they served notice that any signatory nation trying to conceal an underground nuclear test would have to elude a vigorous international verification program armed with the latest monitoring technologies. Thanks to the work of a multidisciplinary Lawrence Livermore team, the international community now has a powerful new forensic tool to help enforce the treaty by detecting even deeply buried clandestine nuclear tests.

Under the terms of the treaty, which bans all nuclear weapons test explosions, a system of verification and inspection will be administered by the Comprehensive Test Ban Treaty Organization in Vienna, Austria.

Lawrence Livermore scientists have long played an important role in providing monitoring technologies in support of nuclear treaty verification and on-site inspection. The latest Livermore technology is based on the discovery that minute amounts of rare, radioactive gases generated in underground nuclear detonations will migrate toward the surface along natural fault lines and earth fissures.

Livermore geophysicist Charles Carrigan led the team that included physicists Ray Heinle, Bryant Hudson, and John Nitao and geophysicist Jay Zucca. With the help of results from earlier studies, they theorized that highly sensitive instruments might detect telltale radioactive gases rising during periods of barometric low pressure through natural fissures in the ground above the blast. To test the hypothesis, the team obtained two gases, 0.2 kilograms (7 ounces) of helium-3 and 50 kilograms (110 pounds) of sulfur hexafluoride, as tracers. These nonradioactive gases are ideal tracers because they are present in very low quantities in the natural environment.

As the photo on p. 45 shows, the bottles containing the gases were placed with a 1.3-kiloton charge of chemical explosives into a mined cavity that was 15 meters (50 feet) in diameter and 5 meters (17 feet) high. The cavity was located 400 meters (1,300 feet) below the surface, two to three times deeper than that required for a similar sized underground nuclear test. A somewhat shallower detonation, says Carrigan, might have produced a collapse crater or extensive fractures connecting the cavity with the surface, both telltale signs of an underground explosion. Hence, clandestine tests would very likely be conducted at the greater depth to avoid easy detection of treaty violations.

Simulating a Nuclear Test

The detonation, known as the Non-Proliferation Experiment, occurred on September 22, 1993, in the rocky Rainier Mesa of the Nevada Test Site, where some of the nation's nuclear tests

were conducted until a testing moratorium went into effect in 1992. The chemical explosion simulated a 1-kiloton underground nuclear detonation, which, as expected, did not produce any visible new cracks in the Earth.

Over the year and a half following the blast, team members, including technical support personnel from Test Site contractors EG&G and REECo, collected nearly 200 samples of subsoil gases for measurement. At some sampling stations, sampling tubes were driven into the ground to depths of 1.5 to 5 meters (5 to 16 feet) along fractures and faults. At other stations, tubes were simply placed beneath plastic sheeting that was spread on the ground to trap rising soil gases and to limit atmospheric infiltration (see photo, p. 46).

The first positive finding came 50 days after the explosion, when sulfur hexafluoride was detected in fractures along a fault. Interestingly, the much lighter helium-3 showed up 375 days—more than a year—following the explosion. Both gases were first detected along the same natural fissure within 550 meters (1,800 feet) of the blast site.

Over the course of the extended sampling period, virtually all the samples yielding concentrations of the two tracers appeared along natural faults and fractures in the mesa during periods of low atmospheric pressure, mainly at the beginning of storms. The low pressure accompanying storms, says Carrigan, makes it possible for the gases to move toward the surface along the faults. Although over the course of a year the number of low-pressure days equal the number of high-pressure days, the gases are eventually drawn upward. "There's a ratcheting effect," he explains. "The gases don't go back down as much as they go up." (See the simulation on p. 46.)

Carrigan notes that it is counterintuitive that helium-3 takes so much longer to make its way up natural fissures than sulfur hexafluoride, which is 50 times heavier. Computer models developed at Livermore showed that this result occurred because most of the heavier sulfur hexafluoride gas moved directly up the rock fractures. In contrast, the helium-3 diffused readily into the porous walls of the rocks as it slowly moved upward toward the soil surface. Critical to determining why helium-3 behaved as it did was Bryant Hudson's analysis of helium-3 in Livermore's noble gas laboratory, where he used mass spectrometry to measure the presence of helium-3 in soil-gas samples down to parts per trillion.

Modeling the Detonation

Carrigan and Nitao modeled the experiment using a porous-flow simulation software called NUFT (Non-Isothermal Unsaturated Flow and Transport) developed at LLNL by Nitao. In attempting to make the simulation as realistic as possible, the team used actual barometric pressure variation data from the Rainier Mesa weather station. The simulation showed the two gases moving at different rates toward the surface following the detonation. The calculated arrival times at the surface for both tracers were in excellent agreement with the data.

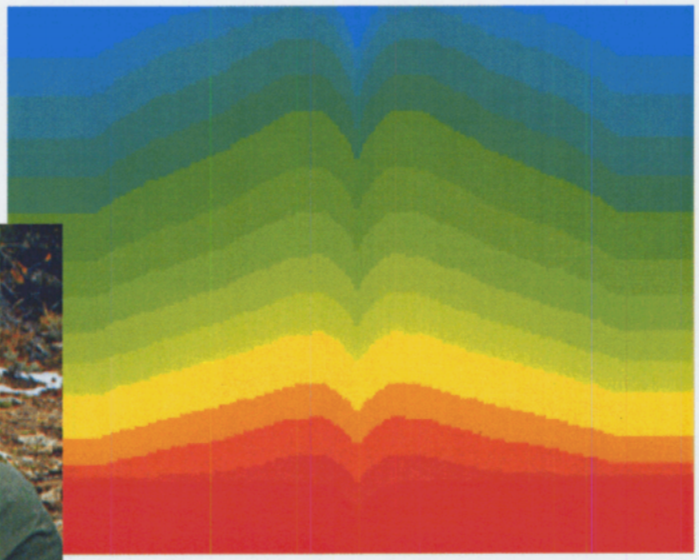
Given the good agreement between the computer model and the observations, the team then used NUFT to simulate the gases released from an underground 1-kiloton nuclear test under atmospheric conditions similar to those that followed the 1993 Non-Proliferation Experiment. The software was used to predict the arrival of detectable concentrations of the rare gases argon-37 and xenon-133 at 50 and 80 days, respectively, after the detonation.

These two isotopes are ideal indicators of nuclear explosions because they are not produced naturally in significant quantities; thus, background levels are extremely low. Also, their short half-lives of 34.8 days and 5.2 days can be used to infer how recently an event had occurred. Other, more long-lived isotopes might still be present in the environment from decades-old tests and would tend to muddy the conclusions of investigators trying to determine whether a clandestine test had recently occurred.

The successful confirmation of the experiment by computer simulation implies that sampling of soil gases for rare, explosion-produced radioactive tracer gases at the surface near a suspected underground test can be an extremely sensitive way

A bottle of sulfur hexafluoride gas is separated from the explosives in a mined test cavity to prevent thermal decomposition of the tracer gas during detonation.

A crew of scientists from Livermore and the Nevada Test Site collect soil-gas samples from tubes inserted to a depth of 5 meters (16 feet) in soils that cover rock containing geologic faults and fractures. The soil gases were detected following a contained, 1-kiloton, underground chemical explosion 400 meters (1,300 feet) beneath Nevada's Rainier Mesa.



Using Livermore's NUFT (Non-Isothermal Unsaturated Flow and Transport) simulation software, the team was able to model gases moving toward the surface following detonation. Shown is a "rainbow" simulation of barometric "ratcheting" of trace gas in the porous walls of a 300-meter- (985-foot-) long, 0.001-meter- (0.03-inch-) wide vertical fracture (centerline of graphic). Concentration decreases from red near the detonation to blue at the surface as surface pressure variations cause the tracer gas to move up and down the fracture until it eventually reaches the surface.

to detect nearby underground nuclear explosions that do not fracture the surface. As a result, says Carrigan, an on-site inspection has a good chance of finding conclusive evidence for a clandestine nuclear explosion for several months afterward.

Putting Treaty Evaders on Notice

"If detected, the radioisotope signals would be unequivocal," according to Bryant Hudson. "They would put treaty evaders on notice that they risk detection if they try to explode a nuclear device underground. We can't absolutely guarantee there won't be cheating, but we've made it more difficult."

Carrigan points out that because of political considerations, it may take some time to get a country to agree to an on-site inspection under the terms of the test ban treaty. The thinking of many experts has been that such inspections need to be conducted within a few days to capture evidence of a test. The Livermore team's work, however, shows that waiting weeks or even months to detect rare gases is not a problem and may well be advantageous, because the gases need time to arrive at the surface.

Team members caution that searching for tracer gases is only one of many detection tools. Other methods that might be used at a suspected test site include analyzing the printouts of seismographs for aftershocks from an explosion, looking for explosion-induced stress in plants and trees, drilling for explosion debris, examining the earth for fractures and craters, and searching for pipes and cables leading underground.

In discussing the work of the team, Carrigan attributes its accomplishments to a confluence of Lawrence Livermore strengths in computer simulation, geophysical theory, nuclear test containment, and radiochemistry. "Interdisciplinary collaboration made this work possible," he says.

—Arnie Heller

Key Words: Comprehensive Nuclear Test Ban Treaty, nuclear proliferation, nuclear treaty verification, NUFT (Non-Isothermal Unsaturated Flow and Transport).

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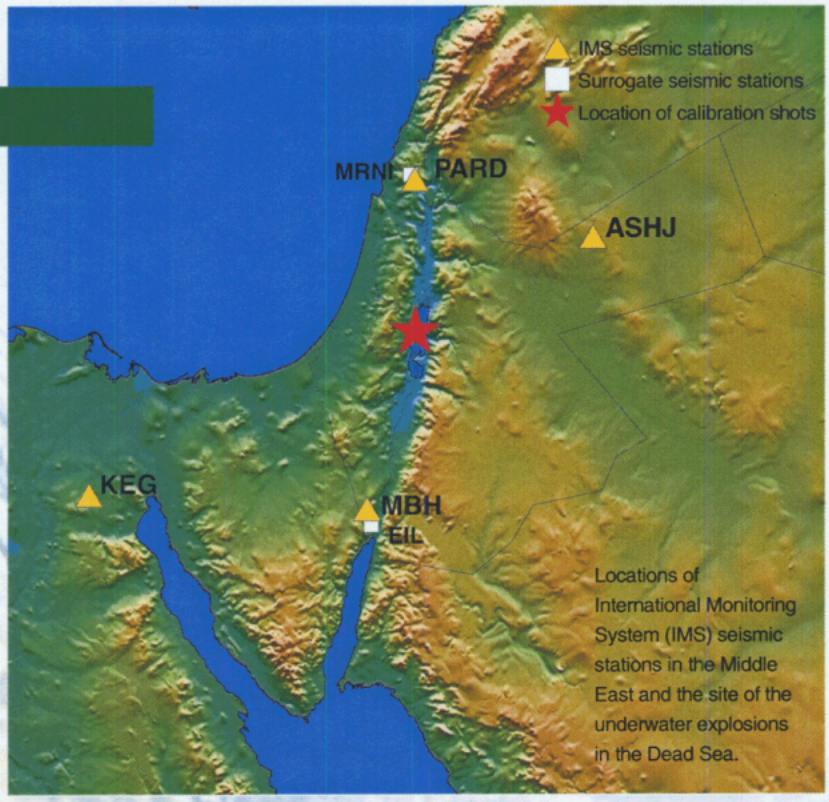
Dead Sea Explosions Trigger International Cooperation



Locations of International Monitoring System (IMS) seismic stations in the Middle East and the site of the underwater explosions in the Dead Sea.

THE Middle East has long been a region beset with tension, if not outright warfare. It is ironic, therefore, that a series of underwater explosions set off in the Dead Sea last November may, with the assistance of Lawrence Livermore seismologists, help to reduce tensions in the area and spur cooperative ventures on geophysical-related issues.

Conducted by the Geophysical Institute of Israel, the explosions were cofunded by Israel and the U.S. Defense Threat Reduction Agency. The main goal was to improve monitoring of the Comprehensive Test Ban Treaty (CTBT) by calibrating Israel's two International Monitoring System (IMS) seismic stations as well as its national system of seismic monitors. Because the tests were announced well ahead of time, other Middle East nations were afforded the opportunity to calibrate their own national seismic stations and any IMS stations on their territories. The explosions will help scientists to pinpoint the location of suspicious seismic events in the area and distinguish them from other sources of seismic signals.

According to Livermore seismologist Keith Nakanishi, detecting, locating, and identifying a clandestine nuclear test poses a particular challenge in the Middle East. International stations are few and far between in the area. Also, a large number of earthquakes and mining explosions generate thousands of seismic signals annually, some quite similar to the signals that would be generated by a small underground nuclear blast.

Additional "ground truth" for the area is sorely needed, Nakanishi says. Ground truth includes seismic data from well-documented earthquakes, mine explosions, or explosions carried out for calibration purposes. Carefully gathered data from these events improve the knowledge of how regional-specific features in the Earth's crust and upper mantle affect the travel times, amplitudes, and frequencies of weak seismic signals. Such data are particularly important to accurately determine the location and origin time of the seismic sources.

Building a Knowledge Base

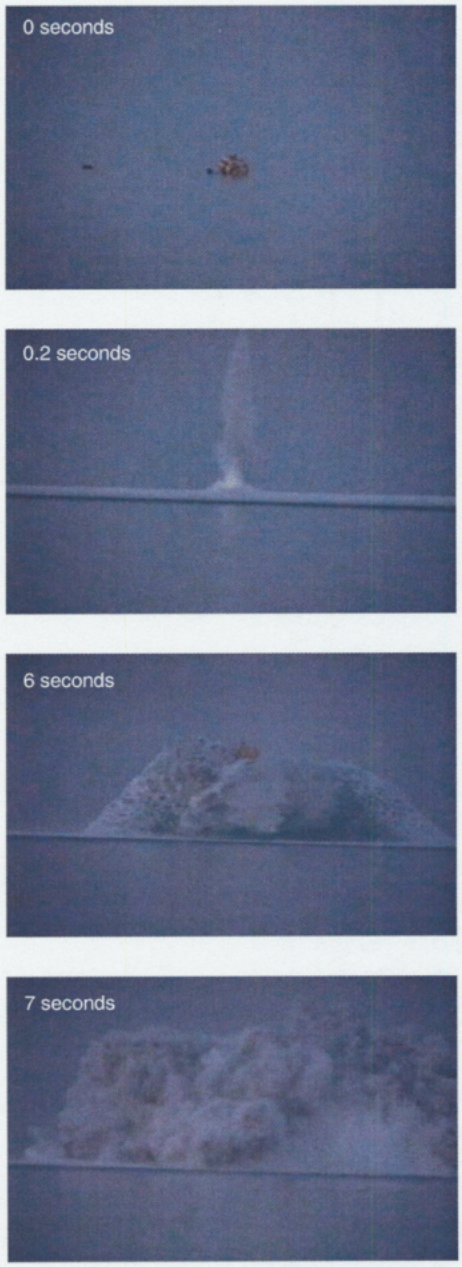
For the past several years, the Department of Energy has been developing a knowledge base of regional seismic properties for the U.S. National Data Center at Patrick Air Force Base, Florida. As part of DOE's program, a team of Livermore experts is focusing on the Middle East and North Africa (called MENA) and the western part of the former Soviet Union. (See *S&TR*, September 1998, pp. 4–11, and *S&TR*, April 1999, pp. 18–20.)

The Livermore team is working to improve techniques to detect and characterize clandestine underground nuclear explosions in key areas of concern for proliferation monitoring. An important application of this technology is for CTBT monitoring. Both Israel and the U.S. have signed the treaty but have not ratified it.

For the Middle East, well-planned calibration experiments are an important means of establishing ground truth in an area whose geologic complexity rivals that of the western part of the United States. Tests conducted in water are preferable to those conducted underground, because water is an excellent medium for transmitting seismic waves. As a result, a much smaller amount of explosives is necessary for a calibration test done under water than is required for an underground test.

The Israelis detonated three underwater packages of explosives, all at the same location (about 5 kilometers from Israel's Dead Sea shores) and depth (about 70 meters below

the water surface). A 500-kilogram explosive was detonated on November 8, 1999, with an approximate magnitude of 2.6 on the Richter scale, and a 2,000-kilogram explosive was detonated on November 10, with an approximate magnitude of 3.5 on the Richter scale.



Stills from a video camera show the sequence of events during the 5,000-kilogram Dead Sea explosive test captured at 0, 0.2, 6, and 7 seconds following detonation. The frame at 0 seconds shows the steel buoy used to fix the charge depth at about 70 meters.

These first two tests were conducted largely to demonstrate that underwater explosions posed no danger to people, property, or the environment. The main test, a 5,000-kilogram explosive package, was set off on November 11, producing a 9-meter-high fountain of water and an approximate magnitude of 4.0 on the Richter scale. (By comparison, a 1-kiloton nuclear explosion would produce a magnitude in the range of about 4.0 to 4.5 on the Richter scale.)

Experiments Were Well Characterized

To be particularly useful, seismic calibration tests must have well-defined locations and origin times. For the Dead Sea tests, these parameters were well determined, says Nakanishi, who attended planning meetings in Israel that focused on such requirements. The location of each test was known to an accuracy of 20 meters, the depth was established to within an accuracy of 5 meters, and the time was determined to an accuracy better than 20 milliseconds.

The explosions were recorded by the Geophysical Institute of Israel and its network of seismic stations, including two IMS stations located in the southern and northern areas of the country. The events were also recorded by a group of more than 30 smaller stations that form Israel's national seismic network and by a few temporary stations Israel installed on the Dead Sea shores. Seismic stations in neighboring countries such as Jordan, Egypt, and Saudi Arabia reportedly also recorded the tests. The Geophysical Institute distributed data electronically to interested parties, including Nakanishi and his colleagues, within a few days.

The Livermore team is analyzing the Dead Sea data and using the results to refine the DOE's knowledge base for the area. For their part, Israel, Jordan, and other Middle East nations are using the data to strengthen their own national means to identify the magnitude and location of any clandestine nuclear blasts and future earthquakes and to better distinguish between the two.

Nakanishi predicts that the explosions will prove as valuable for earthquake monitoring as for CTBT monitoring. "The area is riddled with faults and has a long history of earthquakes dating to Biblical times," he says. The most dangerous fault is the Dead Sea Rift Valley fault that stretches from Syria through Israel and into East Africa, with one fault branch underlying Haifa, Israel. In 1995, an earthquake of magnitude 7.1 on the Richter scale occurred on the fault in the Gulf of Aqaba in the Red Sea near the Israeli city of Eilat.

Well-calibrated seismic networks will allow scientists to better locate the origin of future earthquakes. "By knowing what fault caused the earthquake, we'll know what to expect in terms

of aftershocks," Nakanishi explains. He notes that seismic safety has become a larger concern in the area following the strong 1999 temblors in nearby Turkey.

International Meeting to Focus on Tests

The Dead Sea tests will be the focus of a week-long international workshop to be held this spring, facilitated by Nakanishi and several Livermore colleagues. Each participating nation will share the data recorded at their seismic station. "Jordan and Israel share the Dead Sea," Nakanishi points out. "Each will bring its one-half of the coverage from the tests. By pooling the data, we'll have a full 360-degree coverage."

Nakanishi is hopeful that representatives from Saudi Arabia, Egypt, Jordan, Israel, Cyprus, Lebanon, Turkey, Kuwait, Qatar, Yemen, Oman, and the Palestine Authority will attend. The meeting has the blessing of the U.S. State Department and of the United Nations Educational, Scientific, and Cultural Organization (UNESCO), the meeting's official sponsor.

Nakanishi says that the workshop can also help to reduce political tension. "Regional cooperation in seismology can encourage participation in other technical discussions and increase security in the area," he says. By sharing data and discussing results, participants can be assured that if clandestine nuclear testing is taking place, they would be able to quickly identify it. The data will also help characterize the area for earthquake hazard mitigation and support basic seismic research.

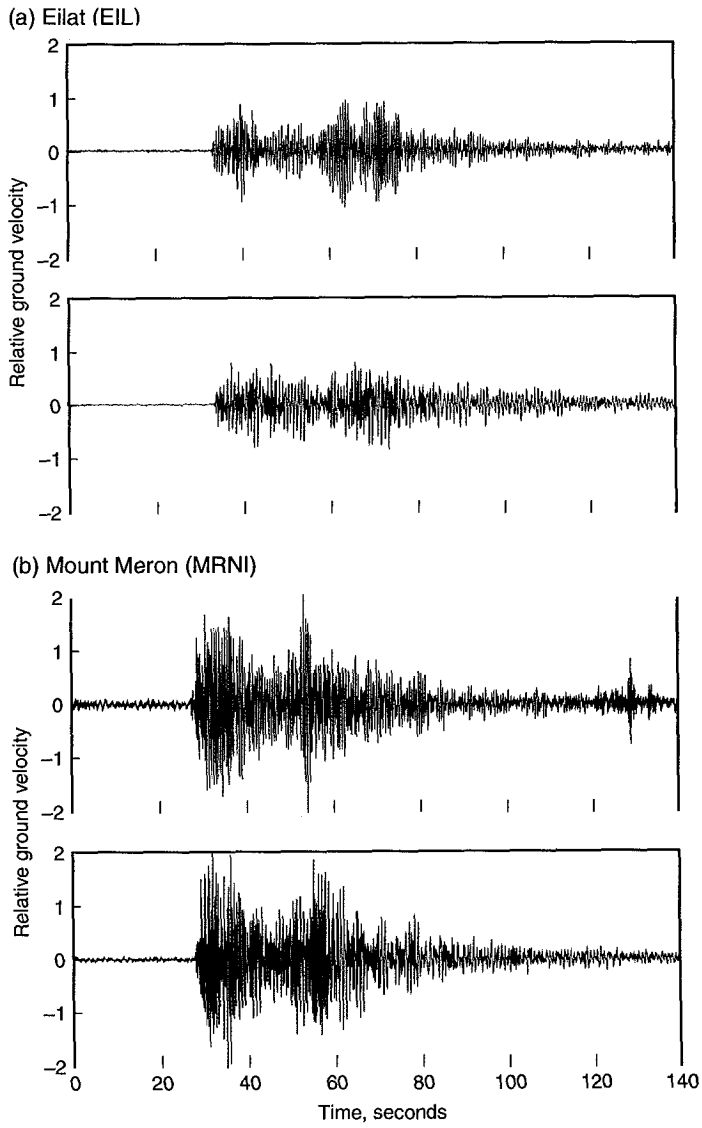
Livermore scientists hosted a similar workshop in 1997 in Cyprus. The focus then was the 1995 Gulf of Aqaba earthquake; interest in the earthquake was high because of its potential negative impact on economic development in the area. "It was a great opportunity for people who don't ordinarily meet to discuss matters of common interest in a neutral venue," says Nakanishi.

He observes that seismic waves respect no boundaries or political or religious beliefs. Because better understanding of ground motion helps every nation, seismology may be a contributor to lessening tensions in an area that has had more than its share of tremors.

—Arnie Heller

Key Words: Comprehensive Test Ban Treaty (CTBT), Dead Sea, Defense Threat Reduction Agency, Gulf of Aqaba, knowledge base, Middle East and North Africa (MENA), seismic monitoring, United Nations Educational, Scientific, and Cultural Organization (UNESCO).

For further information contact Keith Nakanishi (925) 422-3923 (nakanishi1@llnl.gov).



Seismograms from the second and third Dead Sea shots as recorded at Israel's International Monitoring Stations in (a) Eilat and (b) Mount Meron. The locations of these stations are shown on the map on p. 21. (The plots of the first shots are not shown because one of the stations did not provide recordings for the first day.)

Commentary by Wayne Shotts

Tapping the Full Power of Conflict Simulation

WITH the closure of many overseas military bases and the move away from large standing armies and navies, the U.S. military is placing a premium on the use of advanced technology for precision operations that allow U.S. troops to deploy rapidly and win decisively. Lawrence Livermore has a long-standing relationship with the Department of Defense for research and development for advanced defense technologies, and conflict simulation is one area in which we are recognized as among the best in the world. The article beginning on p. 52 describes JCATS (Joint Conflict and Tactical Simulation), the latest advance in decades of effort to create accurate and realistic conflict simulation models.

JCATS is unique in the breadth and depth of the information it integrates and the variety of conflict situations it can simulate. It offers an unprecedented level of detail, operational complexity, and accuracy of simulation. In describing JCATS, it is easy to be swept into the technical details of the model—entity level, aggregation/deaggregation, 660- by 660-kilometer "playbox," and so forth—and lose sight of its wide range of applications and its potential for truly understanding modern combat operations.

The U.S. military uses JCATS primarily for training individual commanders in battlefield operations and tactics. Training, other than "on the job" in actual combat, is difficult to make realistic. Live exercises, which are themselves simulations, are limited by logistics to a relatively small number of participants, and the need for safety limits the use of real weapons. With JCATS, war games can be set up to simulate combat situations, with teams of officers playing the various forces. As the article describes, these war games are extremely accurate and thus provide directly applicable and credible training.

But the program is also useful for mission planning, assessment of military strategy, evaluation of new or proposed technologies, after-action analysis, and even site security assessment.

For example, military doctrine and strategy developed in the large-scale conflicts of the first half of the century are of questionable applicability to current operations, which focus increasingly on limited-scope engagements and peacekeeping. JCATS can be used by military planners to test new doctrines and strategies. It can also be used to evaluate the utility of new technologies, such as alternatives to antipersonnel land mines, or different applications of existing technologies. Once the program's databases are loaded with the desired information (for example, terrain maps, troops, weaponry), simulations can be run over and over again, changing one set of variables at a time. Because JCATS tracks the action at the level of individual items, after-action analyses are extremely detailed, and statistics can be assembled to provide an accurate systems-level view of the pros and cons of different approaches to military operations.

JCATS is also extremely useful for evaluating and improving physical security. Site security at the national laboratories is receiving considerable attention these days. Just as with military training, live exercises to test physical security are expensive and limited in scope. However, JCATS, with its ability to accurately model individual buildings, obstructed lines of sight, the time required to cut through walls or penetrate barriers, and so forth, is ideally suited to this application. Site security has used the program to evaluate the effectiveness of existing physical defenses and response actions against different threats. After-action analyses and statistics, assembled from a large number of runs, provide a credible basis for decisions to alter response tactics or modify physical security features.

Even as the JCATS developers continue to upgrade the model's capabilities, with improvements seemingly limited solely by imagination and technical creativity, the U.S. military and other users are striving to exploit the program's full potential. As new conflict simulation needs arise in both the defense and civil sectors, users will find that the ideal tool is already sitting on their shelves.

■ Wayne Shotts is Associate Director, Nonproliferation, Arms Control, and International Security.

Simulating Warfare Is No Video Game

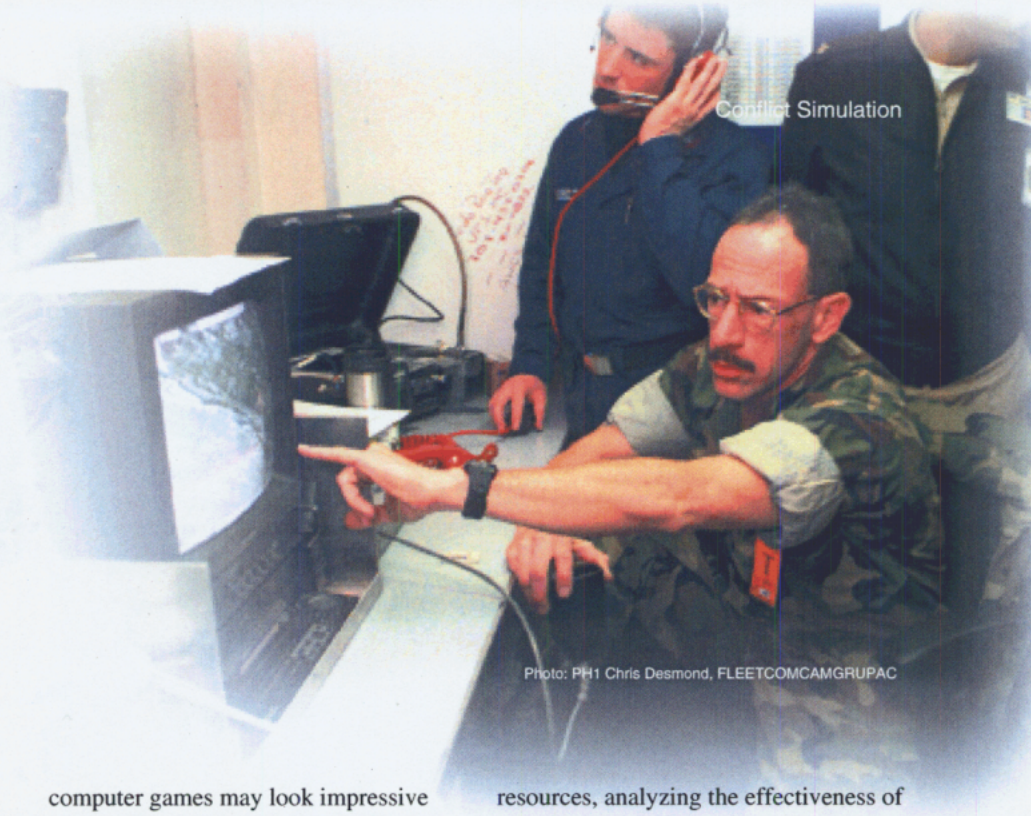
Livermore's JCATS combat simulation program proves invaluable for training officers and rehearsing missions.

Photo: PH2 Jon Gesch, Lawrence Livermore National Laboratory

WITH whirling helicopters, grinding tanks, and screaming soldiers, computer war games have become some of the most popular software programs for video arcades and personal computers in recent years. Long before computers became a household item, however, the nation's armed forces were taking advantage of computer-driven combat simulations to train officers, rehearse missions, and explore tactics.

Since the mid-1970s, Lawrence Livermore computer scientists, working at the Conflict Simulation Laboratory, have pioneered increasingly realistic software for the Department of Defense. The Laboratory's landmark Janus program, developed in the late 1970s, was the first conflict simulation to use a graphical user interface. Since then, Livermore experts have remained at the forefront of combat simulation development by taking advantage of steady advances in hardware and software and by working closely with military officers to understand their needs.

By all accounts, the Livermore simulations have proved highly valuable to the military. They have been employed in Operation Just Cause in Panama and Operation Desert Storm in the Mideast, as well as for combat planning in Somalia, Bosnia, and other international trouble spots.



In 1997, a team of computer scientists from the Laboratory's Nonproliferation, Arms Control, and International Security (NAI) Directorate unveiled Livermore's most powerful combat program. JCATS (Joint Conflict and Tactical Simulation) merged and upgraded the capabilities of two earlier programs, the Joint Conflict Model, an advanced version of Janus, and the Joint Tactical Simulation, an urban conflict model. (See *S&TR*, November 1996, pp. 4–11). Significantly, the program also incorporated important new features requested by its DoD sponsor, the Joint Warfighting Center in Fort Monroe, Virginia, that conferred greater fidelity to the simulations.

JCATS was used to rehearse possible combat options in support of the 1999 Kosovo conflict. It was also used by the Marine Corps and the Navy to plan for and participate in an exercise in the San Francisco Bay Area. During the exercise, JCATS tracked the live participants and tested in real time the effects of virtual air and artillery attacks on the participants.

Taking Physics into Account

Livermore computer scientist Faith Shimamoto, JCATS project leader, notes that every aspect of the program takes physics into account. Typical computer games may look impressive with flashy three-dimensional effects, she says, but they don't always observe the laws of physics.

A typical PC game soldier can jump off a 15-meter cliff without a scratch, but a soldier in JCATS doing the same thing will be badly injured. Neither do commercial games take into account such seemingly mundane but crucial factors as fatigue, inclement weather, low food supplies, or poor visibility. "JCATS realistically simulates the capabilities and limitations of armaments, people, and the environment," she says.

Tom McGrann, deputy leader of the tactical systems section in the Laboratory's Conflict Simulation Laboratory, notes that JCATS is a direct descendant of Janus, building on more than two decades of computer-driven mission analysis and rehearsal experience. "We want to help DoD with software that gives commanders a realistic, cost-effective, and operator-friendly training tool," he says. "Our programs give officers a detailed feel for how combat operations will go, from the deployment of an aircraft carrier to an individual soldier."

The program is currently used for training both individuals and command staffs in tactics and deployment of resources, analyzing the effectiveness of weapons and different force structures, and planning and rehearsing missions. Besides warfighting scenarios, JCATS can also simulate exercises for drug interdiction, disaster relief, peacekeeping, counterterrorism, hostage rescue, and site security. Current users include the Army, Air Force Security Forces, Special Operations Command, Marine Corps, Naval Post Graduate School, U.S. Southern Command, U.S. Army Europe, Department of Energy, and Secret Service.

Program Controls 60,000 Elements

An enhanced version of JCATS released in October 1999 can simulate up to 60,000 individual elements, from soldiers to planes to mob participants. What's more, the new version can run on a workstation as well as on a laptop computer, making it feasible for use in the field.

The new program typically simulates a battle between two opposing sides (often called red and blue forces), but it can accommodate up to 10 sides with friendly, enemy, and neutral relationships. Depending on the rules of engagement established for the conflict, a soldier can be programmed to shoot at the first sign of an opposing force, hide, dig a foxhole,

fire only upon positive identification, or take other action. The rules of engagement may change during the simulation as political alliances shift or when civilians become involved.

Players see only their respective forces and whatever intelligence they acquire about opposing forces by visual or auditory means, including forward scouts, spotter planes, radar, and sensors. A large hill, for example, can prevent a soldier from visually spotting enemy forces massing on the other side. Tanks generate noise that can be "heard" by nearby opposing forces.

Typically, a controller at a master workstation has a bird's-eye view and can observe the movement of forces on all sides. To test players' responses to the unexpected, the controller can resurrect fallen troops, change the weather, provide more fuel, speed up the clock, release a biological weapon, and the like.

Games Can Last Weeks

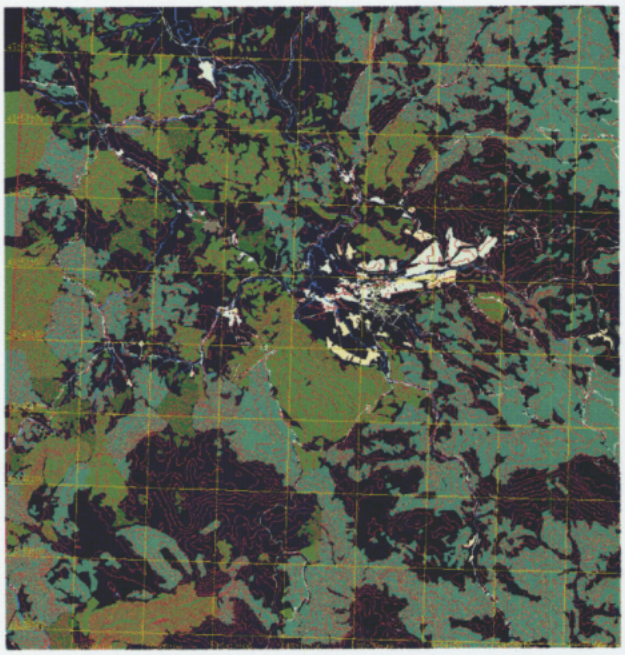
The duration of games varies from 20 minutes for a brief site security exercise involving a few people to two weeks for a complex drug interdiction rehearsal involving different agencies. Sometimes a short game is run dozens of times so that statistical sampling can be used to evaluate a particular tactic or weapon system.

Setting up a JCATS exercise takes one to two weeks depending on the number and kinds of combat forces and, especially, the kinds of topography to be modeled. Terrain is modeled with extraordinary fidelity. Rivers, for example, can be characterized by their current, depth, and underwater obstacles. Players can enter terrain data, including correct elevation and geographical features, from standard DoD maps of the world (such as the one below at the left) and from DoD digitized terrain data.

Players can also import blueprints of specific buildings (below right) for urban warfare and site security exercises. Or users can create their own town or building, as is often done for drug interdiction training. In these cases, JCATS offers a palette of menus to create everything from windows and doors to streets and parks.

Shimamoto points out that terrain significantly affects movement of troops, aircraft, tanks, and maritime operations. A rescue helicopter cannot safely land in a forest, amphibious landing craft must negotiate rocky shores, vehicles move slowly through swamps, and soldiers slow considerably when marching uphill. Environmental factors such as adverse weather, nightfall, and smoke from combat also affect mobility.

JCATS is unusually flexible in the sheer scale of battle, from the defense of a nation involving thousands of



Before a JCATS simulation begins, terrain features are laid out (in this case of the greater Sarajevo area) from standard Department of Defense maps.

Buildings and other urban features are added onto terrain maps. In this example (again of Sarajevo but at a smaller scale), individual buildings can be seen.

soldiers, planes, ships, and vehicles, to the rescue of a hostage in an underground compound by a handful of special operations personnel. Typically, the maximum simulation area, or playbox, is 660 by 660 kilometers, but it can be expanded under special conditions. Even at this enormous scale, a player can zoom in on a city to view details such as roads, rivers, and buildings, and then select an individual building and examine its floor plans.

Depending on the exercise, players have at their disposal a vast range of weapons, including tracked and wheeled vehicles, aircraft and helicopters, ships and submarines, and even systems that are in the development or conceptual stage. Infantry soldiers may have machine guns, rifles, antitank weapons, mortars, and other munitions. Nonlethal weapons, increasingly important as the military assumes peacekeeping duties around the world, include rubber bullets, clubs, tear gas, pepper spray, stinger grenades, rocks, foam, and fists.

Simulations Strengthen Livermore Site Security

The realism of JCATS simulations in urban settings makes it extremely valuable for assessing and strengthening site security at a range of government facilities, including the very institution that created the program. For the past several months, security managers at Lawrence Livermore have been using JCATS to test established interdiction measures against a variety of adversary scenarios. The work has helped to sharpen security strategies, identify vulnerabilities, and train officers for different kinds of threats, even those deemed highly improbable.

Livermore security managers have conducted more than 200 exercises with JCATS, with each exercise repeated about 10 times. According to Stuart Jossey, security administrator with Livermore's Safeguards and Security Department, most of the scenarios involve attempts to gain entry to the Laboratory's heavily guarded Superblock area that houses special nuclear material. Jossey says that JCATS is invaluable for simulating the close-combat, interior fighting conditions a real incursion might involve.

Currently, a small corps of people including Special Response Team members, Protective Force supervisors, and security administrators participate in JCATS exercises at Livermore. The department's long-range goal is to integrate JCATS into the development of site security tactics and training. Operator proficiency requires between two and three weeks of training. "The scenarios involve a lot of mouse clicks under pressure," Jossey notes.

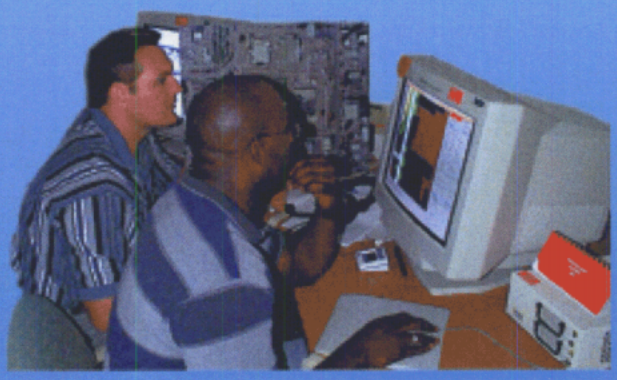
The exercises are performed at adjoining computer stations by operators controlling a designated number of virtual security personnel driving in patrol cars or patrolling on foot. The operators wear headphones to communicate with each other about what their forces see and hear. Their computer screens display buildings comprising the Superblock area and adjoining facilities as well as the location and health of people under their command.

In a nearby room, another operator controls a number of "bad guys" intent, for example, on breaking into a facility containing special nuclear material. This monitor shows only the intruders and any Lawrence Livermore security members they detect. Jossey, meanwhile, operates a station that depicts the locations of all the participants. He can change the makeup of each opposing force, as well as their weapons, on the fly.

Jossey says the simulations are a powerful supplement to real drills involving players with laser-tag-like weapons that are staged regularly in and around the Superblock area. "It's expensive doing actual exercises," he says. "We also run a safety risk because many of our exercises are done at night with people running on roofs, climbing fences, and responding tactically in patrol cars." JCATS allows the department to test security strategies to help decide what scenarios the actual exercises should focus on.

The completed simulations are saved on disk and then replayed for the participants on a large-screen monitor. Jossey invites comments from participants about the exercise, especially how things might have gone better. He also uses the program's Analyst Workstation feature to obtain statistical data such as casualties and ammunition used.

"We get a lot of good statistical information," he says. "The whole point is to make sure we have designed a strategy that denies unauthorized entry to our critical facilities."



Livermore site security exercises use JCATS to strengthen security and help train security personnel for what-if scenarios. Here, Jason Dufour (left) and Raymond Harvey train using JCATS.

Model's Power Is in the Details

Military operations include clearing barriers; aircraft takeoff and landing; bombing runs; naval gunfire; building foxholes, vehicle holes, and fortifications; sandbagging; looking around, standing, and crouching; recovering weapons and ammunitions; resupplying food, fuel, and ammunition; and mounting onto or dismounting from vehicles, ships, airplanes, and helicopters.

The command ship USS *Coronado* docked at a San Francisco pier and served as the command center for both the Navy's and Marine Corps's exercises.

With a feature unique to JCATS, a player may aggregate entities (soldiers, tanks, or other individual units) into a group such as a formation, convoy, squad, or battalion that is then viewed and controlled as one icon. In this way, large formations are more easily viewed and controlled while the program tracks and records activity at the individual entity level. At any moment, a player can zoom in on a squad and examine events involving just a few soldiers, each uniquely outfitted and trained.

The effectiveness of every weapon, from a laser-guided missile to a single bullet, is determined by probability-of-hit and probability-of-kill statistics compiled by DoD. Using these data, JCATS calculates, for example, the blast area and resulting casualties from tripping a land mine. Just as easily, the program calculates if a launched antitank weapon misses the tank, destroys it, incapacitates the tank's movement but leaves its gun free to fire, or destroys the gun but leaves the tank's mobility intact.

Virtual soldiers face hazards from fatigue, enemy and friendly fire, poor health, and inadequate training. Every soldier begins with a certain amount of energy, which is expended more quickly during running or walking uphill. Players can bring in medical assets to attend to the sick or wounded.

In recognition of possible modern enemy capabilities, JCATS can simulate the release of chemical or biological warfare agents as well as other substances that might by employed as poisons during acts of terrorism or warfare. For example, the program can display how exposure to an atmospheric release of a nerve agent can affect personnel. Such capabilities make it useful for developing both military and civilian preparedness and responses.

Many Options to Review a Game

Players can choose from several options to review a completed game. The entire exercise can be replayed at different speeds. The Analyst Workstation, a feature that conducts rapid analyses of exercise data, can also be employed. This capability is especially useful, says Shimamoto, because in combat simulation, only a small fraction of the data is important to any specific factor under scrutiny.

One of JCATS's most significant enhancements is modeling the urban environment for such missions as hostage rescue, disaster relief, mob control, or protecting heads of state along a motor route. In urban settings, players can view

A modular building on the pier housed Marine officers using JCATS to track the action in the Oakland Hills between opposing blue and red forces. The Marines were tied to the command and communication systems headquartered on the nearby USS *Coronado*.

groups of buildings as well as individual building floors and their features—including glass and solid walls, windows, doors, and stairwells—roofs, and underground features, such as tunnels, sewers, and garages. Virtual forces fighting inside buildings are hampered by limited lines of sight, poor lighting, and the risk of injury to civilians.

The program's superb urban simulation capabilities led the U.S. Navy and Marine Corps to give JCATS an important role in exercises conducted last March in the San Francisco Bay Area. The Marine Corps exercise was dubbed Urban Warrior Advanced Warfighting Experiment. Its objective was to develop and test new concepts, tactics, and technologies to prepare Marines for combat in the next century, especially activities in urban areas. The Navy's companion exercise, Fleet Battle Experiment–Echo, also took advantage of JCATS. (See *S&TR*, June 1999, pp. 4–11.)

The exercises were run from the Navy command ship USS *Coronado*, which was docked at a pier in San Francisco. A small building inside the pier housed Marines running JCATS terminals and other command and communications systems. All data were fed to the command ship. Livermore computer scientist Mike Uzelac, director of operations for JCATS, monitored the exercise from the building.

According to McGrann, the Marines focused on an urban exercise because its studies show that by 2020, about 70 percent of the world's population will live in cities and at least 80 percent of those cities will be located within 300 miles of the coastline. Fighting in urban areas, says McGrann, is particularly treacherous because of the danger to the civilian population and because of the numerous hiding places for opponents.

Enemies Eye Urban Warfare

A recent statement by Col. Mark Thiffault, Director, Joint Information Bureau, Urban Warrior, underscores the Marines' commitment to winning urban battles: "Our enemies, having watched Desert Storm on CNN, know they cannot engage the United States with conventional methods. These potential foes view cities as a way to limit the technological advantages of our military. They know that cities, with their narrow streets, confusing layout and large number of civilian noncombatants, place limits on our technological superiority and especially our use of firepower. We have to develop technologies that allow us to win while minimizing collateral damage."

McGrann says that the Marines are concerned about the performance degradation that occurs in standard command, control, communications, computer, and intelligence systems because of cities' concrete buildings, phone lines, and other electronic devices. As a result, Urban Warrior Marines experimented with wireless communications devices, satellite links, remotely piloted reconnaissance aircraft, and global positioning system links.

The focus of the exercise was an intense battle between some 700 battle-dressed Marines, divided into red and blue forces, at the former Oak Knoll Naval Hospital in the Oakland Hills. Both sides wore Multiple Integrated Laser Engagement System gear similar

Photo: PH2 Michelle Hammond, FLEETCOMCAMGRUPAC

Photo: PH3 Eric Logsdon, FLEETCOMCAMGRUPAC

(a) The former Oak Knoll Naval Hospital and adjacent buildings in the Oakland Hills formed the setting for the Urban Warrior Advanced Warfighting Experiment. (b) One Marine demonstrates to another a handheld computer used in the Urban Warrior exercise.

to that used in laser-tag games. Red forces, holed up in the hospital, barricaded stairwells with anything they could find as they tried to fight off blue forces intent on taking over the building.

The fierce battle was set against a backdrop of civil unrest taking place in more than 30 small, adjoining buildings. In this outlying area, additional blue forces kept order among noisy reporters, milling civilians, and rock-throwing agitators, all played by paid actors. (Actual video footage of the exercise can be viewed on the Marine Corps's Urban Warrior Web page at www.defenselink.mil/special/urbanwarrior/.)

Prior to the exercise, Marine Corps personnel, who had previously trained on JCATS, modeled the interiors of the buildings (including the hospital's 9 stories and 500 rooms) by digitizing construction blueprints and entering the data into the program's "terrain editor." The Marines' Integrated Global Positioning System Radio System provided updates every 30 seconds on the position of vehicles and soldiers outside buildings. Because the radio system is ineffective inside buildings, every hospital room was wired with the Inside Building Instrumentation System to keep track of each Marine's location and health status (healthy, wounded, or killed) when they were inside.

The ever-changing data on the Marines' locations were broadcast from the Oakland Hills on secure communication links and fed into JCATS for viewing on screen. In this way, command personnel on the pier and aboard the USS *Coronado* were provided unprecedented, real-time details about the location of their Oakland forces, including the whereabouts of combatants on every floor of the hospital.

Virtual Strikes Complete Exercise

JCATS also simulated the effects of artillery and tactical air strikes that obviously could not be used in the Oakland area. Computer-generated weapons even included systems that currently exist only in concept. The virtual strikes were executed by a Marine JCATS operator in San Francisco, acting on request by an officer at the battle and approved by an operation commander.

The program calculated the time of flight and the effects based on the impact of the virtual strike and the reported location of the live participants. In this way, commanders learned within seconds the effects of using these weapons. Back in Oakland, both red and blue participants were quickly informed through their laser tag and radio gear if they had been wounded or killed by the virtual strikes.

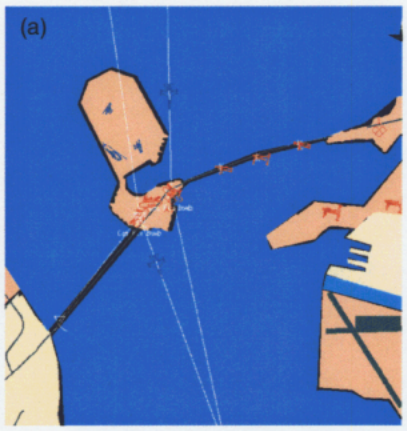
While the battle for control of the hospital raged, JCATS simulated combat on Treasure Island in San Francisco Bay and on the San Francisco–Oakland Bay Bridge. Red forces driving toward Oakland were attacked by blue virtual aircraft. Simulated Navy ships just off the coast were also included in the overall conflict.

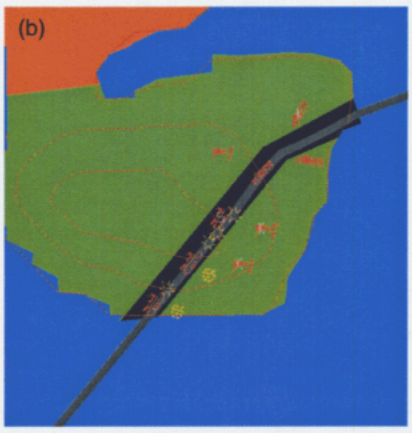
Following the exercise, the program provided a thorough review for the command officers. The review showed who was killed and how and when they became casualties, thereby removing much of the uncertainty that often surrounds the lessons-learned process following an exercise.

Uzelac says that the Marines were pleased with the usefulness of JCATS. In particular, "They recognize that combining simulated firepower with live participants allows the Marines to significantly broaden their training missions," especially when environmental or safety restrictions prevent the actual use of weapons. Uzelac adds that the Marines plan to use the program in their next urban exercise, which will incorporate more buildings than were used in Oakland.

The Livermore team is already working on enhancements to JCATS that have been requested by the Joint Warfighting Center. These enhancements will include an

This JCATS image depicts the location of blue forces outside the Oak Knoll Hospital as well as inside one of its nine floors. (K stands for kill or destroyed target.)





JCATS also simulated combat on Treasure Island in San Francisco Bay and on the San Francisco–Oakland Bay Bridge. (a) Red forces heading toward Oakland were attacked by blue virtual aircraft and Navy ships. (b) Detail of Treasure Island combat. The yellow sunbursts and star shapes depict the effects from naval gunfire and air strikes, respectively. (K stands for kill or destroyed target; S stands for suppressed.)

information warfare capability, a terrain-generation capability using computer-aided design building files and satellite imagery, and better integration with military communication systems.

Shimamoto notes that one of JCATS's most important advantages is its applicability to all the military services. Although each military service has its own weapons, its own methods of combat operations, and even its own specialized simulation programs, JCATS is a powerful resource for all of them. Because it models all of the services' forces, as well as those of other security organizations, it also encourages better coordination among agencies, both in planning missions and in training officers. "We've made JCATS as powerful and flexible as we know how to help the nation prepare for conflicts in the new century," she says.

—Arnie Heller

Key Words: combat simulation, Conflict Simulation Laboratory, Fleet Battle Experiment–Echo, Janus, JCATS (Joint Conflict and Tactical Simulation), Joint Conflict Model, Joint Tactical Simulation, Joint Warfighting Center, U.S. Marine Corps, Special Response Team, U.S. Navy, Urban Warrior Advanced Warfighting Experiment.

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About the Scientist

FAITH SHIMAMOTO joined Lawrence Livermore in 1975 while working on her master's thesis in electronics engineering at the University of California at Davis, where she also earned a B.S. in electronics engineering. She has provided computational capabilities development and management support to numerous departments in the Engineering and Computation directorates, recently managing teams in the development of miniature sensor technology for low-Earth and suborbital satellite experiments.

Currently, she is the project leader of the Joint Conflict and Tactical Simulation (JCATS) Conflict Simulation Laboratory in the Nonproliferation, Arms Control, and International Security Directorate. She is responsible for leading the development of JCATS, a real-time simulation program used by the departments of Energy, Defense, and Transportation for training, analysis, and mission planning, particularly in an urban environment. Her responsibilities have included software development and testing and coordination of deliverables with JCATS's primary proponent, the Joint Warfighting Center. She has also developed JCATS for and demonstrated it to other potential users and sponsors.

Commentary by Anthony Carrano and Wayne Shotts

Deploying Livermore Resources against Biological Weapons

TEN years ago, the consuming national security threat to the U.S. was the nuclear arsenal of the Soviet Union. Virtually all of the energies, talent, and resources of the Laboratory were dedicated to checkmating the Soviet threat, both by ensuring a safe and reliable U.S. nuclear stockpile and by contributing to bilateral strategic arms control agreements. That world no longer exists. The Soviet Union has disappeared, and although a Russian nuclear threat remains, it is greatly diminished, and prospects are favorable for a continuing good relationship with Russia.

Today, the highest priority threat to national security and U.S. forces stems from the proliferation of nuclear, chemical, and biological weapons—the so-called weapons of mass destruction (WMD). Possible perpetrators include rogue states, state-sponsored terrorist groups, domestic terrorists, and even internationally organized criminals and narcotics traffickers. Indeed, more than 50 countries are known to supply, demand, or provide a conduit for WMD devices, materials, and technology.

New technologies and capabilities are needed to deal with the WMD proliferation threat, and nowhere is this more true than for biological weapons. The revolution in bioscience and biotechnology has both heightened awareness of the threat posed by biological weapons and provided the basis for tools to counter it.

The Department of Energy recently established the Chemical and Biological Weapons Nonproliferation Program and is encouraging its rapid implementation and growth. Lawrence Livermore, in cooperation with other national laboratories, is taking an active part in this effort by developing diagnostic methods, detection instrumentation, modeling analyses, and decontamination procedures that prevent and respond to the threat posed by chemical and biological weapons. The Laboratory has many existing capabilities—in remote sensing, detection technologies, forensic science, intelligence analysis, atmospheric science, process modeling systems analysis, hazardous material handing, and bioscience—to apply against this threat. The article beginning on p. 62 reports on specific examples of how Livermore is using these existing capabilities to respond to the bioweapons threat.

The early 1990s saw the development of miniaturized, portable detection instruments at Livermore, and this effort was enhanced in 1996 by a Laboratory Directed Research and Development project to specifically develop instruments for rapid field identification of biological agents. This project culminated in a demonstration of outstanding performance by several biodetectors in Joint Field Trials held at the Dugway Proving Grounds, Utah. On the basis of this success, the Nonproliferation, Arms Control, and International Security and the Biology and Biotechnology Research Program directorates have expanded a collaborative initiative to address the threat of biological weapons.

The principal elements of this effort are systems analysis, biodetector development, and molecular diagnostics. A systems analysis team is working with federal and local representatives to determine where to deploy detectors and to develop incident response scenarios; these activities also provide valuable information for improving biodetector performance and operation. In biodetector development, researchers are continuing to decrease the size and increase the sensitivity of the instruments, with an emphasis on autonomous detection systems or "sentries." Molecular diagnostics research is contributing to the fundamental understanding of biological threat organisms needed for optimum incident response and attribution. This information will also be used to improve pathogen detection assays and to assist other agencies in the development of effective preventative and therapeutic medical treatments.

As a national security laboratory, Lawrence Livermore is building on its established programs and its historical nuclear weapons mission to address the threat posed by biological weapons. This most recent initiative typifies the Laboratory's multidisciplinary, cross-cutting approach to applied science and its ability to anticipate and respond to national security needs.

■ Anthony Carrano is Associate Director, Biology and Biotechnology Research Program.

■ Wayne Shotts is Associate Director, Nonproliferation, Arms Control, and International Security.

Reducing the Threat of Biological Weapons

Livermore's strategy for defense against the use of biological weapons integrates technology, operations, and policy and provides a framework for coordinated local, state, and federal emergency response.

"WEAPONS of mass destruction" is a terrifying term. We all have mental images of the horrors of a nuclear attack, and photos of Kurdish and Iranian casualties of Iraqi chemical attacks attest to the devastation of chemical weapons. The third weapon of mass destruction—the biological weapon—has been around at least since the Middle Ages when soldiers catapulted the bodies of dead smallpox victims over fortress walls in the hope of infecting their enemies or at least demoralizing them.

Lately, biological weapons have been appearing in the news with increasing frequency. The anthrax threat in Las Vegas in February of this year is an example. Surplus stores in Las Vegas sold out of gas masks, and talk-radio shows were swamped with callers asking about evacuation points. That threat turned out to be a false alarm, but the next one might be real.

Biological agents are of concern in part because of the ease with which many of them can be manufactured, transported, and dispensed. And because of the lag time between a biological attack and the appearance of symptoms in those exposed, biological weapons could be devastating. Many biological agents are contagious, and during this lag time, infected persons could continue to spread the disease, further increasing its reach. Hundreds or even thousands of people could become sick or die if a biological attack were to occur in a major metropolitan area.

With the knowledge that several nations have produced and perhaps also deployed biological warfare agents, Congress in 1996 passed the Defense Against Weapons of Mass Destruction Act, which authorizes the Department of Energy to establish a Chemical and Biological Weapons Nonproliferation Program. Under this and similar programs, Lawrence Livermore and other laboratories and institutions are working together to increase this country's capabilities to detect and respond to an attack by biological or chemical weapons.

Beginning as recently as Fiscal Year 1996 with a Laboratory Directed Research and Development strategic initiative, Livermore has rapidly expanded its chemical and biological nonproliferation program and is now playing a lead role in this effort, particularly as it pertains to defense against biological weapons. The Laboratory is applying its investment in biological science, engineering, microtechnology, computer modeling, systems analysis, and atmospheric science to a number of programs designed to improve the country's response to a biological attack. Personnel from departments and directorates across the Laboratory are at work on:

- Advanced detection systems to provide early warning, identify populations at risk and contaminated areas, and facilitate prompt treatment.
- Biological forensics technologies to identify the agent, its geographical origin, and/or the initial source of infection.
- Methods for predicting the transport

of biological agents in urban environments and for assessing the area and duration of the hazards associated with a biological attack.

• New decontamination technologies to clean and restore facilities without causing further environmental damage.

Livermore is working closely with the U.S. military, various government agencies, and such major cities as New York City and Los Angeles to ensure that the results of these biological nonproliferation efforts meet the needs of military troops, the FBI, local law enforcement personnel, fire fighters, public health officials, and others who would likely be first on the scene following a biological attack. Together these groups are answering questions to help create the best, most task-appropriate, and most usable system possible. For example, how accurate do sensors have to be? What level of false alarms can be tolerated? Where will sensors be located—in buildings, on emergency response personnel, or at other sites? How much training will be feasible for emergency response personnel on the use of sensors and decontamination agents—that is, how user-friendly must these processes be?

Livermore is developing a strategy for defense against the use of biological weapons that integrates technology, operations, and policy and provides a framework for coordinated local, state, and federal emergency response.

Better Detection Systems

A key factor limiting the nation's ability to protect against a biological attack has been the state of biodetector technology. Only now is technology becoming available that permits identification of biological organisms within minutes, when concentrations are low but often still dangerous. Before the revolutions in genomics, biotechnology, microengineering, and microcomputers, such identification could only be done in a laboratory and took days to weeks. Soon, however, technology advances—many of them made at Lawrence Livermore—will offer the possibility of rapid, accurate, and sensitive biodetectors for use in battlefield or urban settings.

Figure 1. Ray Mariella, Jr., working with a multichambered PCR (polymerase chain reaction) unit. In the 1997 Advanced Concept Technology Demonstration, this PCR instrument proved an effective tool for field identification of the DNA in nonvirulent bioagent simulants.

Automation Is Key

Livermore is developing two types of fully automated biodetectors for real-time sample collection, detection, and identification in the field. A miniature flow cytometer (known as miniFlo) uses an immunoassay system to look at the proteins and other material on the surface of cells, and a portable PCR (polymerase chain reaction) unit identifies the DNA inside the cell. (See the box on p. 64 for more information on these systems.) Because of their small size and efficiency, both units process data much faster than their laboratory-scale cousins, while maintaining the highest level of sensitivity.

To fully automate sample collection and preparation, Livermore is developing and testing components for an aerosol biocollector and a microfluidic sample preparation system. The device will collect and sample particles in the air, including biological agents, if present. To maximize detection potential and give faster results, the PCR unit and miniFlo are also being "multiplexed" to handle multiple samples at once. Other system improvements are being made to both instruments to lower the rate of false positives (false alarms), increase the sensors' sensitivity, and make the systems even smaller, more rugged, and less reliant on consumables than they are now. Livermore expects to have continuously operating, integrated biosensors available for use within the next few years.

With two types of sensors working in tandem, the chance of false alarms will be reduced considerably. Tolerance for false alarms differs greatly for military versus civilian situations. Deployed troops are already in a state of heightened readiness, with protective equipment available and the training required to react to attack situations. In contrast, with civilians, false alarms could lead to injuries and perhaps to dismissal of future legitimate alarms. Thus the military may be able to afford some level of false alarms, but the goal for the civilian sector is no false alarms.

The miniFlo and the PCR systems have proved their mettle against established performance criteria at the U.S. Army's international Joint Field Trials at the Dugway Proving Grounds in Utah. At Dugway, participants use a variety of instruments to detect simulant materials representative of typical biological weapon materials.

At the 1996 Joint Field Trials III, miniFlo was superb at detecting *Bacillus globigii* and *Erwinia herbicola* (nontoxic simulants for anthrax and plague respectively) at various low concentrations. Overall, miniFlo detected 87% of all unknowns with a false alarm rate of under 0.5%. At the 1997 Port/Airbase Advanced Concept Technology Demonstration and the January 1998 Dugway Joint Field Trials IV, the portable PCR unit clearly demonstrated the potential of PCR as an effective technique for field identification of DNA (Figure 1).

Networked Detectors

A networked system of these or other biodetectors could provide U.S. troops in the field with early warning of a biological attack. That is the goal of a project for the Department of Defense known as JBREWS (Joint Biological Remote Early Warning System), on which Livermore is collaborating with Johns Hopkins Applied Physics Laboratory and Los Alamos National Laboratory. As shown in Figure 2, JBREWS will consist of a network of sensors and communication links. By tying this network into the military's existing communications systems, JBREWS will take advantage of well-established command and communications procedures. Initially equipped with commercially available sensors, JBREWS is being configured so that improved biodetectors can be incorporated into the system as they become available.

Livermore is responsible for what is known as "C4I"—command, control, communications, computers, and intelligence. The Laboratory is developing the connectivity between the sensors and the control station, the software for all sensors, and an automatic analysis and reporting system that runs up through the military chain of command. JBREWS is scheduled to be demonstrated in a Department of Defense Advanced Concept Technology Demonstration in 1998.

Biological Forensics at Work

If a bacterium or spore appears in a collected sample, how will a biodetector know what it is? The key to identification will be a library of "signatures" of the makeup, function, and DNA of various biological agents that will be stored on a microchip in the detector, together with pattern-matching software and code for reporting results. This technology will allow advanced detectors in the laboratory and ultimately in the field to quickly match the signatures of collected particles to signatures in its memory, in much the same way that fingerprints are matched.

Building on years of experience in genomics and biotechnology, Livermore scientists are expanding the

Livermore's New Biodetectors

Portable PCR

In late 1996, Lawrence Livermore delivered to the U.S. Army the first fully portable, battery-powered, real-time DNA analysis system. DNA analysis requires many copies of a DNA sample, which are made by the polymerase chain reaction. PCR requires repeated cycles of an aqueous sample being heated close to the boiling point and then cooled. To detect DNA in a sample, a synthesized DNA probe or primer tagged with a fluorescent dye is introduced into the sample before it is inserted into the heater chamber. Each probe or primer is designed to attach to a specific organism—anthrax, plague, etc. If that organism is present in the sample, the probe attaches to its DNA. By measuring the sample's fluorescence, the instrument reports the presence (or absence) of the targeted organism.

In Livermore's portable unit, the thermal cycling process takes place in a micromachined, silicon heater chamber that has integrated heaters, cooling surfaces, and windows through which detection takes place. The PCR reaction and DNA analysis take place in a disposable polypropylene reaction tube inserted into the heater chamber.

Because of the low thermal mass and integrated nature of Livermore's silicon heater chambers, they require very low power and can be heated and cooled much faster than conventional units. So the unit is not only portable but also much faster and more energy-efficient than bench-top models. A multiple-chamber unit that allows the examination of many samples at the same time has been field tested.

MiniFlo

Livermore's miniature flow cytometer is the latest in a series of flow cytometers developed over the past two decades in Livermore's Biology and Biotechnology Research Program Directorate. Flow cytometers are used in laboratories to analyze cells and their features, perform blood typing, test for diseases and viruses, and separate out particular cells or chromosomes. What sets miniFlo apart from other flow cytometers is its small size, portability, and sensitivity.

These features are made possible by a novel system that eases the alignment and increases the accuracy of flow cytometry. In a flow cytometer, the cells flow in single file in solution while the experimenter directs one or more beams of laser light at them and observes the scattered light, which is caused by variations in the cells or DNA. Instead of using a microscope lens or an externally positioned optical fiber as a detector, this method uses the flow stream itself as a waveguide for the laser light, capturing the light and transmitting it to an optical detector. This approach not only eliminates the alignment problems that plague traditional flow cytometers but also collects ten times more light than a microscope lens does. Simpler alignment and more light mean better, faster analysis.

Bacteria are large enough for individual detection in the miniFlo, but viruses and proteins are not. So beads large enough to be detected are coated with an antibody and added to the sample. The virus or protein attaches itself to the bead and can then be detected. When different beads are coated with different antibodies, simultaneous detection of several biological agents is possible.

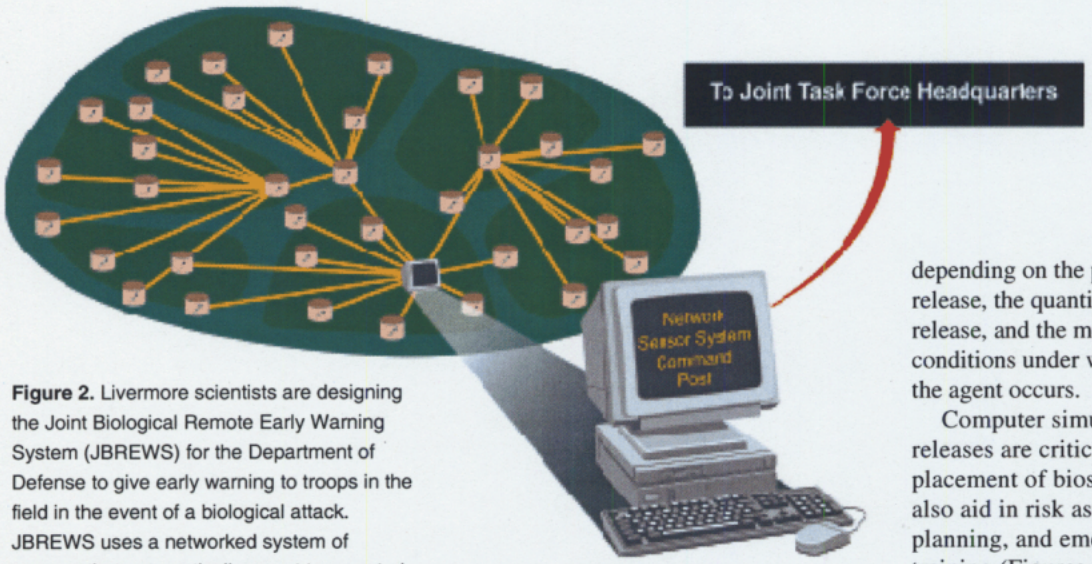

Figure 2. Livermore scientists are designing the Joint Biological Remote Early Warning System (JBREWS) for the Department of Defense to give early warning to troops in the field in the event of a biological attack. JBREWS uses a networked system of sensors that automatically report to a central computerized command post.

information base of the DNA sequences of biological agents to enable rapid, unambiguous identification of biological agents. To facilitate this process, they are developing ways to speed up the process of finding unique DNA sequences among organisms.

A process known as representational difference analysis helps to identify unique DNA sequences. Parts of the DNA of two organisms are mixed. If they stick together, they match; if they do not stick, they are unique parts. Currently, this process is cumbersome and slow, but Livermore scientists are working to automate it to be able to examine many sequences in parallel.

Another project is studying specific pieces of bacterial DNA and examining the possibility of using their location as an indicator of differences among strains. A third project is investigating virulence factors, which are the genes that give a biological organism its infectivity or toxicity. If a bioweapon is being genetically engineered, those genes might be moved to an unnatural host in an attempt to thwart detection and identification.

In addition to identifying the particular agent being used, tools being developed at Livermore also seek to provide information that will help to identify the perpetrator of a biological attack. Livermore biomedical researchers were among the first to study regional differences among the various naturally occurring strains of anthrax and other biological agents. Law enforcement personnel will be able to match data about a pathogen with data on regional or strain characteristics (indicators of engineered characteristics) and with data on worldwide biological research, epidemiology, and infectious diseases and respond to the threat.

Predicting Agent Dispersion

The ability to accurately predict the dispersion, concentration, and ultimate fate of biological agents released into the environment is essential to prepare for and respond to a biological agent release. Of particular concern is the threat to civilian populations within major urban areas where potential terrorist incidents are more likely to occur. There the hazard from a biological-agent release could be confined to a localized area within or around a single building or extend out to a large portion of the city or even into the surrounding suburbs, depending on the particular agent release, the quantity and duration of the release, and the meteorological conditions under which dispersion of the agent occurs.

Computer simulations of biological releases are critical to the design and placement of biosensor systems. They also aid in risk assessment, disaster planning, and emergency response training (Figures 3 and 4). If a biological release were to occur, real-time predictions of agent concentrations would be used to characterize the source, estimate exposure levels, identify affected areas and best evacuation routes, and later assist with decontamination. Accurate information about the likely course of a bioagent attack is key for emergency response managers, who must notify health officials, inform emergency response teams, and make public safety decisions.

The urban biological release problem is quite complex and requires modeling capabilities that are still in the early stages of development and application. For example, models of airflow inside buildings and subways have been developed to some degree but do not accurately incorporate the decrease in airborne concentration that results from deposition of the toxic material on walls, ceilings, ventilation ducts, and other interior surfaces. Similarly, computational fluid dynamics models of the highly distorted flows and dispersion patterns created by complexes of buildings are just beginning to include the effects of biological aerosols (gravitational settling, deposition, and viability degradation) and multiple building interactions.

Lawrence Livermore, Lawrence Berkeley, Los Alamos, and Argonne

national laboratories are working together to develop an integrated and validated atmospheric modeling capability for biological agent releases in an urban environment. They will be applying these models to case studies in a range of release scenarios, from closed office buildings, to subway systems, to stadiums and street corners. The goal is to make the models applicable to real-life situations and ultimately to integrate them into the incident response capability of the National Atmospheric Release Advisory Center, located at and operated by Lawrence Livermore.

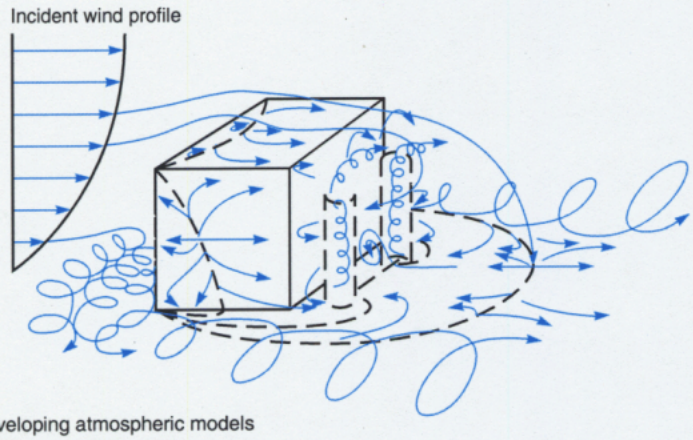

Figure 3. Developing atmospheric models for an urban setting requires taking many flow patterns into consideration. As shown here, air movement around just one building is highly complex.

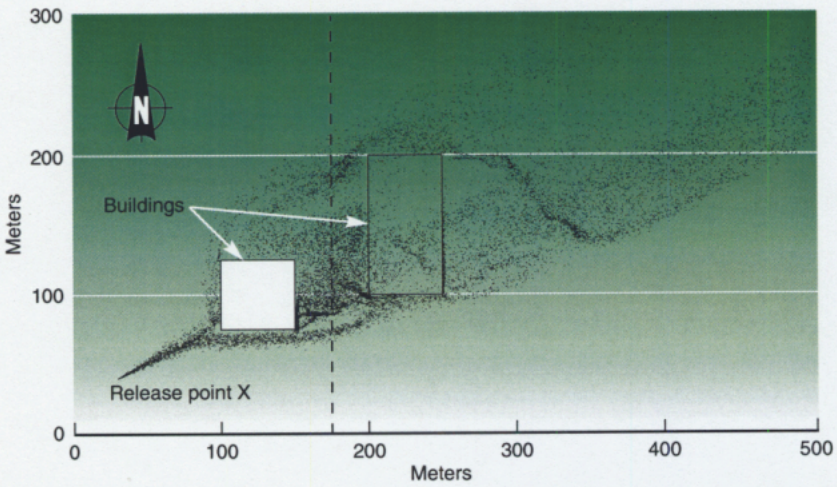

Figure 4. This scenario shows where particles will be 10 minutes after they are released at point X in a 240-degree (west southwest) wind of 10 meters per second. Several areas of high particle concentration are visible to the south of the two buildings, with lesser concentrations to the north and to the east.

Decontaminating a Site

After an area has been exposed to a biological attack, it must be decontaminated before it can be reopened to the public. Livermore and Los Alamos national laboratories are working together to develop decontamination strategies for three scenarios—an open stadium, a semi-enclosed subway, and an enclosed area such as an office or home. Certain decontamination methods might be acceptable for one scenario but not another. For example, more corrosive reagents and large volumes of water might be acceptable in a stadium but could not be used in an office building.

Plain household bleach is one of the best decontamination agents around, and it is used regularly in biological laboratories throughout the country. But 5% sodium hypochlorite (as bleach is more technically known) is a very caustic product, so it must be used with care. The team is working to develop decontamination methods that are as effective as bleach but more acceptable environmentally.

Decontamination proceeds in several stages, from cleanup of gross contamination such as puddles of agent, to localized decontamination of walls or furniture that were directly exposed to the agent, to cleanup of ductwork or inaccessible cracks for hidden contamination, and finally to long-term remediation such as special paints or sorbents to destroy small quantities of agent that are left after completion of other decontamination. These stages may require different cleanup materials. A variety of liquids and powders are being studied, as is an array of delivery methods such as foams and gels. One treatment method that has been found to be effective and more environmentally acceptable than hypochlorite (an alkaline product) is peroxymonosulfate, which is an acidic oxidizer. Figure 5 compares treatment of a simulant for anthrax with these

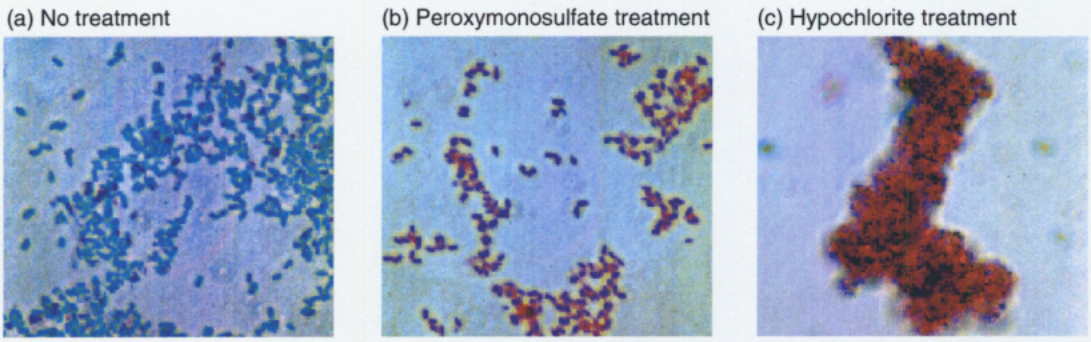

Figure 5. *Bacillus globigii* spores (a simulant of the spores that cause anthrax) are shown (a) before and (b) after a 30-minute exposure at 22°C to peroxymonosulfate, an acid oxidizer, and (c) after treatment with hypochlorite, an alkaline oxidizer. Spores were stained with malachite green (blue-green) and safranin (red) dyes. Safranin dye penetrates only dead spores because of their damaged walls, thus making it a good indicator of the effectiveness of a biocide.

oxides. The selected method must be not only effective but also easy to use with minimal training.

The social and political issues involved in decontamination and reentry to a site are not being overlooked. Central to these concerns is "How clean is clean enough?" The team is coordinating with the biosensor developers to devise sampling and analysis systems that can verify that decontamination is complete.

One hurdle for the decontamination process is that no real-time biodetector currently under development at Livermore uses an assay that can distinguish between viable organisms and dead or decontaminated ones. Work has begun on a "viability assay" based on flow cytometry to provide this important piece of information so that decontamination can proceed in a timely manner.

Responding to the Threat

The threat of biological weapons is all too real, and the U.S. must be prepared to respond if a bioattack occurs on the battlefield or in a civilian setting. During the 1991 Gulf War, the U.S. had no systems available for rapid, timely field detection of bioagents. The situation today is very different. The military has deployed Biological Integrated Detection Systems (BIDS), which can tentatively identify the presence of a suspected biological agent in the field and warn soldiers to take appropriate action to protect themselves against the agent, pending positive laboratory identification. And there are also programs such as Livermore's that include new detection, identification, atmospheric modeling, and decontamination capabilities, which, combined with work by others on better vaccines and medical treatment, are bringing the country to a level of preparedness that can meet a biological threat.

—Katie Walter

Key Words: biodetectors, bioinformatics, biological warfare agents, decontamination, DNA analysis, flow cytometry, genomics, miniFlo cytometer, National Atmospheric Release Advisory Center (NARAC), polymerase chain reaction (PCR), weapons of mass destruction (WMD).

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About the Scientist

FRED MILANOVICH received his B.S. in physics from the United States Air Force Academy in 1967 and a Ph.D. in applied physics from the University of California at Davis in 1974. He is currently program manager for the Chemical/Biological Nonproliferation Program within the Nonproliferation, Arms Control, and International Security Directorate at the Laboratory. This program is providing an integrated response to the emerging threat of chemical and biological terrorism with innovation in detection technology, bioinformatics, fate and transport analyses, and incident response. Milanovich has published extensively in his field and holds many patents for optical sensors and measurement instruments. His research interests also include trace biodetection, laser spectroscopy, analytical instrumentation development, and microtechnology.

Uncovering Bioterrorism

DNA-based signatures are needed to quickly and accurately identify biological warfare agents and their makers.

WITH the end of the Cold War, the threat of nuclear holocaust faded but another threat emerged—attack by terrorists or even nations using biological agents such as bacteria, viruses, biological toxins, and genetically altered organisms. The former Soviet Union once had a formidable biological weapons program. Now, several countries and extremist groups are believed to possess or to be developing biological weapons that could threaten urban populations, destroy livestock, and wipe out crops.

Even terrorists with limited skills and resources could make biological weapons without much difficulty, says Tony Carrano, Lawrence Livermore's associate director for Biology and Biotechnology Research. "It's not complex, it's not expensive, and you don't need a large facility." For these reasons, biological weapons have been dubbed the poor man's atomic bomb.

Contributing to the ease of making and concealing biological weapons is

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the dual-use nature of materials to produce such weapons, because they are found in many legitimate medical research and agricultural activities as well. CIA Director George Tenet touched on this topic in Congressional testimony in February when he noted the overlap between manufacturing vaccines and producing biological weapons.

The agents used in biological weapons are difficult to detect and to identify quickly and reliably. Yet, early detection and identification are crucial for minimizing their potentially catastrophic human and economic cost. Lawrence Livermore scientists are participating in the Department of Energy's program to improve response capability to biological (as well as chemical) attacks on the civilian population.

A major part of DOE's program is developing better equipment, both fixed and portable, to detect biological agents (see *S&TR*, June 1998, pp. 4–11). However, any detection system is dependent on knowing the signatures of organisms likely to be used in biological weapons. These signatures are telltale bits of DNA unique to pathogens (disease-causing microbes). "Without proper signatures, medical authorities could lose hours or days trying to determine the cause of an outbreak, or they could be treating victims with ineffective antibiotics," says Lawrence Livermore's Bert Weinstein, deputy associate director of Biology and Biotechnology Research.

Because of the importance of biological signatures, DOE has launched a biological foundations program as a key thrust of its effort to improve response to terrorist attacks. The program involves experts at the Lawrence Livermore, Brookhaven, Los Alamos, and Sandia national laboratories, as well as colleges and universities. Researchers from the four national laboratories get together at least quarterly to share information and yearly for a formal review of their work. Weinstein reports that important progress has been made since the program began in early 1997, and new signature sets are being transferred to the Centers for Disease Control and Prevention and the DOE.

Over the next several years, DOE scientific teams expect to produce species-level signatures for all of the most likely biological warfare pathogens. The teams also expect to have an initial set of species-level signatures for likely agricultural pathogens, because an attack on a nation's food supply could be just as disruptive as an attack on the civilian population.

Several Levels of Signatures

The teams also aim to develop strain-level signatures for the top suspected agents. Strains are a subset of a species, and their DNA may differ by about 0.1 percent within the species. A species, in turn, is a member of a larger related group (genus), and its DNA may differ by a percent or so from that of other members of the genus.

Characterizing pathogens at the strain level requires significantly more work than recognizing a species. But strain-level signatures are essential for determining the native origin of a pathogen associated with an outbreak; such information could help law enforcement identify the group or groups behind the attack.

The biological foundations work aims to provide validated signatures useful to

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public health and law enforcement agencies as well as classified signatures for the national security community. In developing these signatures, biological foundation researchers are also shedding light on poorly understood aspects of biology, microbiology, and genetics, such as immunology, evolution, and virulence. Increased knowledge in these fields holds the promise of better medical treatments, including new kinds of vaccines.

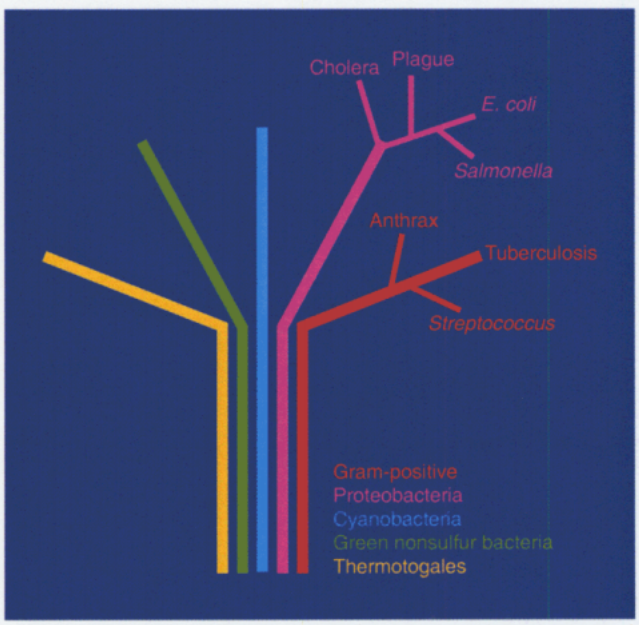
The biological foundations work is one element in DOE's Chemical and Biological Nonproliferation Program. Livermore's component of this work is managed by its Nonproliferation, Arms Control, and International Security Directorate. Other components of the overall program include detection, modeling and prediction, decontamination, and technology demonstration projects.

Livermore researchers were among the first to recognize, in the early 1990s, the tremendous potential of detectors based on DNA signatures. "We knew that a lot of work was necessary to develop the signatures the new detectors would need," says Weinstein. In particular, the researchers recognized several pitfalls. For example, if signatures are overly specific, they do not identify all strains of the pathogen and so can give a false-negative reading. On the other hand, if signatures are based on genes that are widely shared among many different bacteria, they can give a false-positive reading. As a result, signatures must be able, for example, to separate a nonpathogenic vaccine strain from an infectious one.

Several Levels of Identification

To enhance their detection development effort, researchers are exploring advanced methods that distinguish slight differences in DNA. They are using the multidisciplinary approach that characterizes Livermore research programs. In this case, DNA signature development involves a team of microbiologists, molecular biologists, biochemists, geneticists, and computer experts. In addition, the Livermore work benefits from collaborations with experts worldwide, extensive experience with DNA sequencing, and affiliation with DOE's Joint Genome Institute (see *S&TR*, April 2000, pp. 4–11).

Much of the work is focused on screening the two to five million bases that comprise a typical microbial genome to design unique DNA markers



This phylogenetic tree is a simple representation of the bacterial kingdom. All human bacterial pathogens belong to the Gram-positive (red) or Proteobacteria (magenta) divisions. The other divisions consist of nonpathogenic bacteria associated with diverse environments. Biological signatures must be able to differentiate infectious bacteria from hundreds of thousands of harmless ones. Each genus of bacteria has many species, and each species can have thousands of different strains.

DNA signature development involves a multidisciplinary team of microbiologists, molecular biologists, biochemists, geneticists, and computer experts. Here, biomedical scientists Peter Agron and Lyndsay Radnedge are performing suppressive subtractive hybridization to distinguish DNA of various species of virulent organisms.

that will identify the microbe. The markers, called primer pairs, typically contain about 30 base segments and bracket specific regions of DNA that are a few hundred bases long. The bracketed regions are replicated many thousands of times with a detector that uses polymerase chain reaction (PCR) technology. Then they are processed to unambiguously identify and characterize the organism of interest.

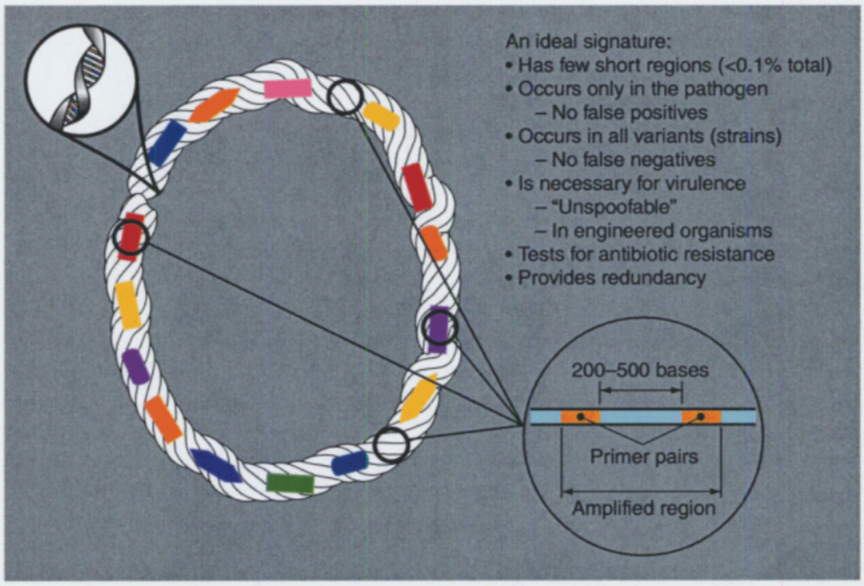
Weinstein notes that different signatures will be needed for different levels of resolution. For example, authorities trying to characterize an unknown material or respond to a suspected act of bioterrorism will begin with fairly simple signatures that flag potentially harmful pathogens within a few minutes. Typically, such a signature would encompass one or two primer pairs and be sufficient for identification at the genus level (*Yersinia* or *Bacillus*, for example) or below.

A signature in the next level of resolution is needed for unambiguously identifying a pathogen at the species level (*Yersinia pestis*, for example). This signature involves about 10 primer pairs. Currently, it takes several days to obtain conclusive data for a species-level signature. The goal is to reduce that time to less than 30 minutes.

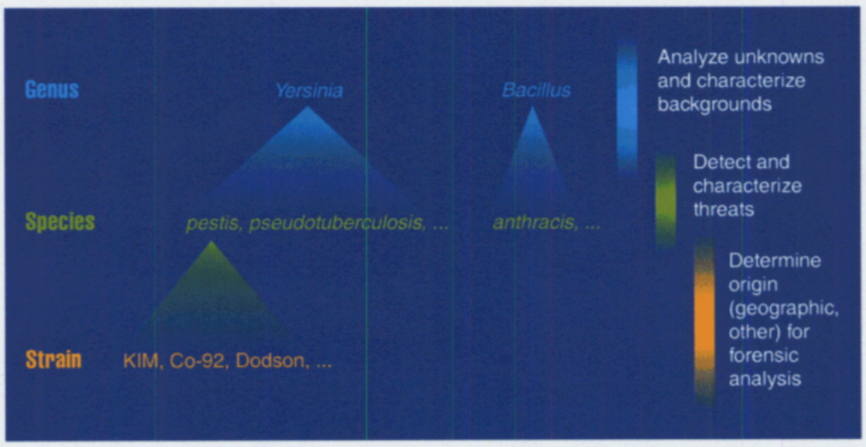
The third signature level is used in pathogen characterization, identifying any features that could affect medical response (for example, harmless vaccine materials versus highly virulent or antibiotic resistance pathogens). This signature level involves some 20 to 30 primer pairs. Together, the primer pairs offer a certainty of correct identification. Currently, providing such a high level of confidence requires several days; the goal again is to reduce the time to less than 30 minutes.

The final signature level, intended primarily for law enforcement use, will permit detailed identification of a specific strain of a pathogen (for example, *Yersinia pestis* KIM) and correlate that strain with other forensic evidence. Such data will help to identify and prosecute attackers. The present typical time lag for results is currently a few weeks, and the goal is to reduce that to a few days.

Biological foundations program scientists have worked with DOE and other agencies to assemble a list of natural pathogens most likely to be used

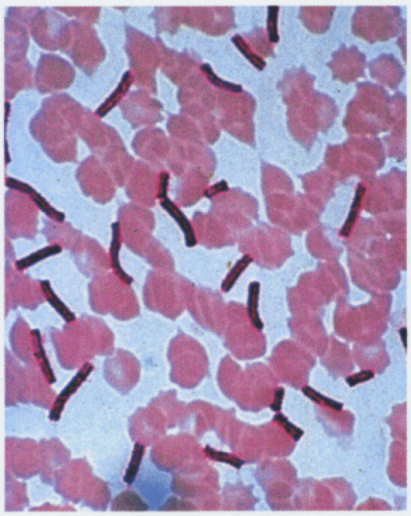


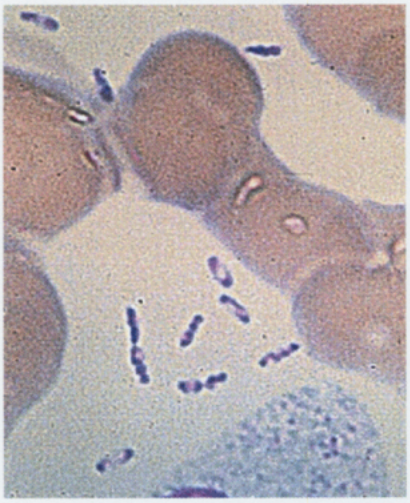
Bacterial chromosomes (DNA) form loops, unlike human chromosomes which form strands. In the loop, between two to five million bases of bacterial DNA are screened to locate unique regions (circled), which are marked with primer pairs. The marked regions are amplified thousands of times using polymerase chain reaction technology and then processed to identify and characterize an organism.



Different levels of signature complexity provide different problem resolutions. A simple signature, involving only one or two unique DNA marker regions, provides genus-level identification. Signatures for species- and strain-level identifications involve more marker regions and take longer to process, but provide more detail and accuracy. Law enforcement uses require signatures that provide strain-level identification.

in a domestic attack. The list includes bacteria, viruses, and other classes of threats, such as agricultural pathogens. Two extremely virulent pathogens head the list: *B. anthracis* and *Y. pestis*, which cause anthrax and plague in humans, respectively. *Bacillus anthracis* has few detectable differences among its strains, whereas *Y. pestis* strains can vary considerably in genetic makeup. Unraveling the significant differences between the two organisms will give national laboratory researchers experience vital for facing the challenges of the next few years, as they develop signatures for a wide spectrum of microbes.





Two extremely virulent organisms head the list of pathogens most likely to be used by terrorists: *B. anthracis* (top) and *Y. pestis* (bottom), which cause anthrax and plague in humans, respectively.

Livermore Focuses on Plague

Research has been divided and is carefully coordinated among laboratories to avoid duplication. Livermore researchers are focusing on *Y. pestis*, *Francisella tularensis* (a bacterium causing a plaguelike illness in humans), and several other microbes that threaten human and animal health. They are working in collaboration with the U.S. Army Medical Research Institute of Infectious Diseases, the Centers for Disease Control and Prevention, the California Department of Health Services, Louisiana State University, Michigan State University, and research centers in France, China, and Russia. "We want to be prepared for the most likely pathogens from throughout the world," says Weinstein.

Eleven species and many thousands of strains belong to the *Yersinia* genus. The most notorious species, *Y. pestis*, causes bubonic plague and is usually fatal unless treated quickly with antibiotics. The disease is transmitted by rodents and their fleas to humans and other animals. Although rare in the U.S., cases are still reported in the Southwest.

Livermore researcher Emilio Garcia notes that the seemingly subtle DNA differences among many *Yersinia* species mask important differences. One species causes gastroenteritis, another is often fatal, and a third is virtually harmless; yet all have very similar genetic makeup. Garcia's team is using a technique called insertion-sequence-based fingerprinting to understand these slight genetic differences. Insertion sequences are mobile sections of DNA that replicate on their own. Analyzing for their

Biological Warfare Has a Long History

The use of biological agents as weapons is not a new phenomenon, Lawrence Livermore's Tony Carrano points out. The Romans, for example, used corpses of diseased animals to poison the drinking wells of their enemies. During the horrific Black Death of the Middle Ages, the bodies of bubonic plague victims were catapulted over fortress walls of besieged cities.

During the French and Indian wars, 1754–1763, the British gave smallpox-infested blankets as gifts to the Indians because of their suspected alliance with the French. During World War II, Germany and Japan produced bacteria capable of infecting humans.

Biological attacks in the United States have been few and isolated. One occurred in 1984, when followers of Baghwan Shree Rajneesh poisoned several salad bars in Oregon with salmonella bacteria. In Europe, terrorist groups in Germany began producing botulinum toxin. In the late 1980s in Japan, the Aum Shinrikyo cult acquired anthrax bacteria and botulinum toxin and attempted to collect samples of Ebola virus.

Following the 1991 Persian Gulf War, United Nations inspectors revealed the vast scope of Iraq's biological arsenal. Iraq was found to possess more than 150 bombs and 25 missile warheads filled with botulinum toxin, anthrax, or aflatoxin. What's more, Iraq had built sophisticated laboratories to study and produce a wide range of biological agents and toxins.

presence will not only help refine signatures for *Y. pestis* but also shed light on how microorganisms evolve into strains that produce lethal toxins. This understanding, in turn, should give ammunition to researchers seeking an antidote or vaccine.

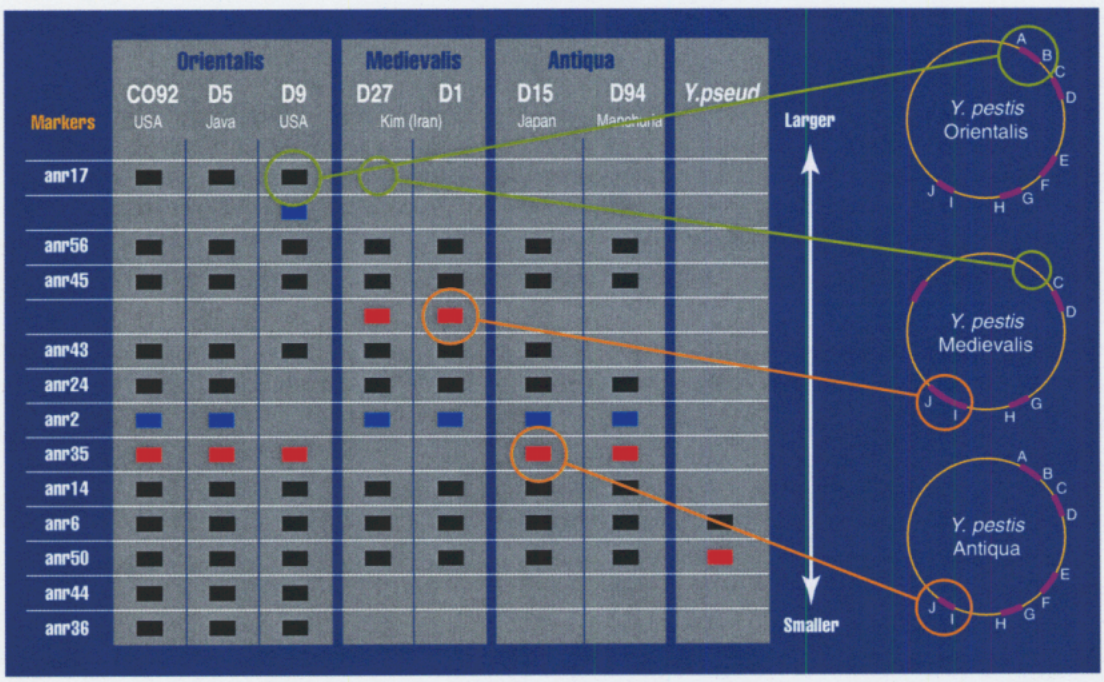
Garcia's team is collaborating with other world-renowned research centers to better understand the genetic differences among species and strains. A collaboration with France's Pasteur Institute is comparing the genetic complement of *Y. pestis* with another member of the *Yersinia* group (*pseudotuberculosis*) that causes an intestinal disease. "They are closely related, and yet they cause such different diseases," Garcia says.

Better and Faster, with More Uses

Livermore scientists are using a number of methods that allow more rapid identification and characterization of unique segments of DNA. Each method has advantages and drawbacks, with some more applicable to one organism than another. Weinstein expects that within two years, the Livermore team will have settled on a handful of techniques as the workhorses of signature generation.

In addition to the insertion sequence method, another promising technique is called suppressive subtractive hybridization. The method takes an organism and its near neighbor, hybridizes the DNA from both, and determines the fragments not in common as the basis of a signature. A team headed by Lawrence Livermore biomedical scientist Gary Andersen is working with colleagues at Moscow State University in Russia to advance the technique; one goal is to simultaneously analyze 96 strains of DNA.

Andersen's team has used suppressive subtractive hybridization to distinguish the DNA of *Y. pestis* from that of *Y. pseudotuberculosis*. The team has also used the technique to aid California's poultry industry by providing a handy way to detect *Salmonella enteritidis*. This bacterium can cause illness if eggs are eaten raw or undercooked. Subtractive hybridization results have been so successful that the signature can now be



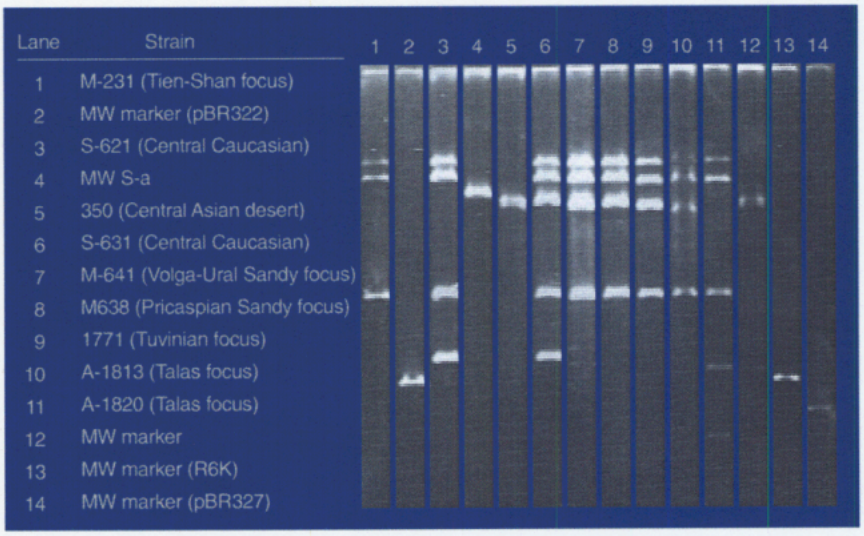
Insertion sequences are repeated sections of DNA whose location in the chromosome varies between different strains. Analyzing for their presence provides information about the type and biological function of a strain. The table at above left shows differences in the insertion sequence "fingerprints" of *Y. pestis* strains associated with the last three plague outbreaks. Red and blue rectangles indicate fragment shifts and changes from strain to strain. Some of these differences are graphically represented in the three strains of *Y. pestis* diagrammed at above right. For example, a fragment found in Orientalis is absent from Medievalis, and a fragment in Antiqua has shifted and become shorter than what it was in Medievalis.

used to distinguish between subtypes of salmonella bacterium.

In addition to the DNA-based pathogen detection methods, researchers are developing detection capabilities using antibodies that can tag a pathogen by attaching to a molecular-level physical feature of the organism. Antibody assays are likely to play an important role in pathogen detection because they are generally fast and easy to use (commercial home-use medical tests use this form of assay).

Biological foundation researchers are working to improve these detection methods as well. For example, a collaboration with the Saratov Anti-Plague Institute in Russia is studying a bacteriophage (bacteria-killing virus) that only attacks *Y. pestis* and none of its cousins. Researchers recently discovered that the virus produces a unique protein component to attach to the bacterium cell wall at a certain site and gain entry. Garcia says that recognizing the distinct site could form the basis of a foolproof antibody signature. "If it's possible to achieve it with *Y. pestis*, we may be able to do it with other pathogens," he adds.

A Lawrence Livermore team has aided California's poultry industry with a biological signature to detect *Salmonella enteritidis*, a bacterium that can cause illness if eggs are eaten raw or undercooked. The signature can distinguish between subtypes of the bacterium and their different pathways to humans and other hosts.



Russia's Saratov Anti-Plague Institute is an important collaborator with Livermore in elucidating the subtle genetic differences among strains of *Y. pestis*. Above are some of the strains isolated by the institute.

Sensing Virulence

As more information about pathogens and their disease mechanisms becomes available and as genetic engineering tools to transplant genes become cheaper and simpler to use, the threat of genetically engineered pathogens increases. Biodetectors must be able to sense the virulence signatures of genetically engineered pathogens, or they will be blind to an entire class of threats. "Our ultimate objective is to identify several specific virulence factors that might be used in engineered biological warfare organisms so that we can detect these engineered organisms and break their virulence pathway," says Weinstein.

One key factor useful for detecting engineered organisms is an antibiotic resistance gene. When transplanted into an infectious microbe, the gene could greatly increase the effectiveness of a biological attack and complicate medical response. Some antibiotic resistance genes are widely shared among bacteria and are easily transferred with elementary molecular biology methods. In fact, a standard biotechnology research technique is introducing antibiotic resistance genes into bacteria as an indicator of successful cloning. "We need to be able to rapidly recognize such genes so that the medical response is appropriate," says Weinstein.

Another telltale indication of genetic tampering is the presence of

virulence genes in a microbe that should not contain them. Virulence genes are often involved in producing toxins or molecules that cause harm or that simply evade a host's defense. "If a series of genes is made available to perform their functions at the right time, they could cause real damage," says Lawrence Livermore molecular geneticist Paula McCready. If interfering with the action of one of these genes or its proteins interrupts the virulence pathway, the disease process can be halted. Identifying and characterizing important virulence genes and determining their detailed molecular structure will greatly aid the development of vaccines, drugs, and other medical treatments.

As an example, *Y. pestis* disables the immune system in humans by injecting proteins into macrophages, one of the body's key defenders against bacterial attack. Because the protein acts as an immunosuppressant to disable the macrophage, understanding its structure not only would help scientists fashion a drug that physically blocks the protein but also would shed light on autoimmune diseases such as arthritis and asthma. A Lawrence Livermore team led by Rod Balhorn is working to determine the three-dimensional shapes of toxins such as the one produced by *Y. pestis* (see *S&TR*, April 1999, pp. 4–9).

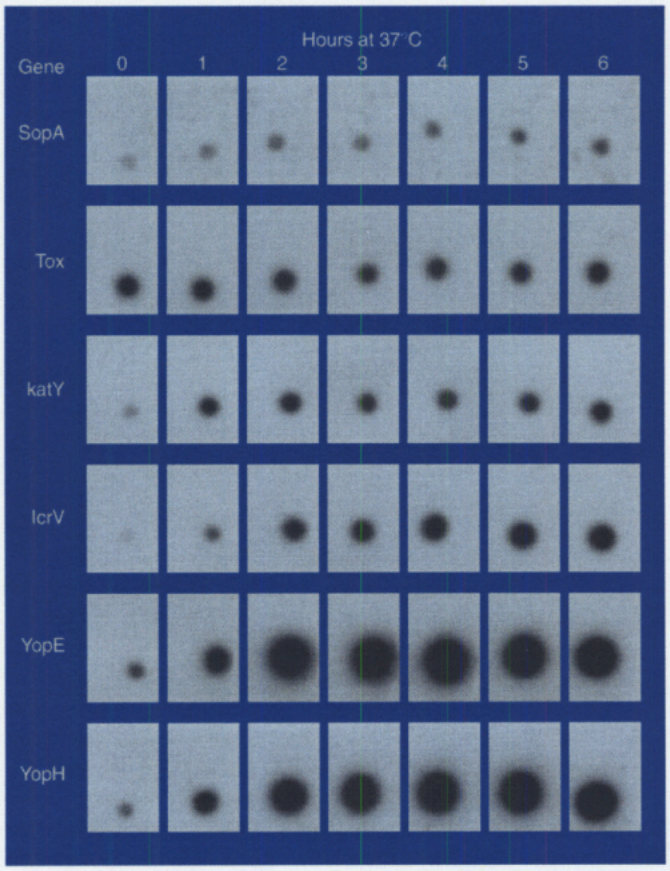
Virulence Genes in Common

Virulence genes spread naturally among pathogens and thus are also found in unrelated microbial species. Therefore, virulence genes alone are not sufficient for species-specific DNA-based detection. "We have to differentiate the virulence genes in natural organisms from engineered organisms," says Garcia.

Livermore researchers are using different methods for differentiating virulence genes from among the thousands of genes comprising the genomes of pathogens. One technique looks for genes that "switch on" (start making proteins) at the internal temperatures of mammals. For example, Livermore scientists are studying genes of *Y. pestis* that become much more active at 37°C. It seems a safe bet that many of these genes are associated with the bacterium multiplying within a warm-blooded host.

In 1998, a Lawrence Livermore team made an important contribution to understanding the genetics of *Y. pestis*. They sequenced the three plasmids (bits of DNA located outside the microorganism's circular chromosome) that contain most of the virulence genes required for full development of the bubonic plague in animals and humans. Plasmids sometimes transfer their genes to neighboring bacteria in what is called lateral evolution. (Antibiotic resistance genes are also located on plasmids.)

Garcia, who led the plasmid sequencing team, says that studying virulence genes can shed light on how new strains develop. The *Y. pestis* strain that causes bubonic plague, for example, may have evolved some 20,000 years ago. Such understanding is relevant to HIV, which may not have become infectious for humans until the 20th century.



As a way of identifying virulence genes, Livermore researchers look for bacterial genes that produce proteins at the internal temperatures of mammals (37°C). Four such genes (katY, IcrV, YopE, and YopH) in *Y. pestis* become much more active over a 6-hour period at 37°C.

Working with End Users

McCready notes that there needs to be a strong relationship between development of biological signatures and detection technologies and their end uses. Livermore researchers work with agencies that will be using signatures from Livermore and Los Alamos for both handheld detectors and field laboratories. "We want to make sure our tools get to the experts and agencies that need them," she says.

McCready is working closely with colleagues at the Bioterrorism Rapid Response and Advanced Technology Laboratory of the federal Centers for Disease Control and Prevention. Livermore is collaborating with the CDC to make diagnostic tools available to regional public health agencies and thus create a national mechanism for responding quickly to bioterrorism threats. Currently, many health agencies use detection methods that are not sufficiently sensitive, selective, or fast. For example, one culture test for detecting anthrax takes two days. Major damage and even death may have occurred in that time.

McCready emphasizes that DNA signatures will be thoroughly validated before being released, because their use might lead to evacuations of subways, airports, or sporting events, and such evacuations cannot be undertaken lightly. As part of the validation effort, Livermore scientists are characterizing natural microbial backgrounds to make sure that the signatures are accurate under actual conditions. To that end, researchers are collecting background microbial samples in air, water, and soil, as well as in human blood, urine, and saliva. McCready points out that *B. anthracis* is related to *B. thruginensis*, a naturally occurring harmless microbe that lives in dirt and can give a false positive reading to anthrax if the signature used is not adequately specific. The characterization effort is being aided by a device called the Gene Chip. Manufactured by Affymetrix Inc. and using technology developed by Livermore, the device simultaneously monitors the expression of thousands of genes.

Livermore researchers are looking ahead to a time when their efforts will have helped to equip federal and state agencies with a robust set of biological signatures crucial for America's response to any biological warfare threat. Equally important, the researchers envision a strong mechanism linking biomedical scientists with public health and law enforcement officials to develop new signatures speedily and cost-effectively to stay several steps ahead of terrorists.

—Arnie Heller

Key Words: anthrax, bacteriophage, biological signatures, biological weapons, Centers for Disease Control and Prevention (CDC), DNA, Gene Chip, plague, plasmids, virulence.

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About the Scientist

BERT WEINSTEIN is the deputy associate director of Livermore's Biology and Biotechnology Research Program (BBRP) Directorate. He received his B.S. in physics and mathematics from Brigham Young University and his M.S. and Ph.D. in physics from the University of Illinois at Urbana. He currently serves as leader of the biological foundations thrust area for the DOE Chemical and Biological Nonproliferation Program and as liaison for BBRP with the DOE Joint Genome Institute in Walnut Creek, California. At the Laboratory since 1974, he has held both research and leadership positions in four major programs: inertial confinement fusion, nuclear design, intelligence and national security, and the biology and biotechnology research program. He also served as a member of the Science Council for the Department of Energy's Office of Nonproliferation and National Security (now the Office of Defense Nuclear Nonproliferation).

A National Strategy against Terrorism Using Weapons of Mass Destruction

THE World Trade Center and Oklahoma City bombings signaled a change in the character of terrorism in the U.S. Most of the previous acts of domestic terrorism have not involved mass casualties. However, recent incidents indicate an apparent desire of terrorists to injure or kill large numbers of innocent people—six people were killed and more than 1,000 injured in the World Trade Center bombing, and 168 people died in the bombing of the Alfred P. Murrah Federal Building.

As horrifying as these acts of terrorism were, damage and casualties could have been much greater if the terrorists had used weapons of mass destruction (WMD)—nuclear, chemical, or biological weapons. In March 1995, the Aum Shinrikyo cult demonstrated that terrorists can acquire WMD with its sarin nerve gas attacks in the Tokyo subway that killed 12 people and sickened more than 5,000.

An open society like ours in the U.S. is particularly vulnerable to WMD terrorism. Information on nuclear, chemical, and biological weapons is readily available on the Internet and in many how-to books. There is increasing evidence of illegal trafficking in nuclear materials. In addition, a number of countries hostile to the U.S. are known to be developing WMD capabilities, and some of them are known to support terrorist groups.

Livermore Study Group Formed

In June 1996, the Director of Central Intelligence and the Deputy Secretary of Energy chartered a study of the threat posed by terrorist groups using nuclear, chemical, or biological weapons in the U.S. Organized by Lawrence Livermore with Associate Director Wayne Shotts as the sponsor, the group was chaired by R. James Woolsey, former Director of Central Intelligence, and Joseph S. Nye, Jr., former Assistant Secretary for Defense for International Security Affairs. Known as the Livermore Study Group, it included eminent experts from the Central Intelligence Agency, the Departments of Defense and Energy, the Federal Bureau of Investigation, the Arms Control and Disarmament Agency, Congress, U.S. industry, and academia.

The study group examined the potential of terrorist use of WMD against the U.S., reviewed current U.S. capabilities, and made recommendations for enhancing the nation's ability to prevent and respond to this threat.

U.S. Poorly Prepared for WMD Terrorism

The study group concluded that the U.S. is ill-prepared to respond to a terrorist attack that uses WMD. According to co-chair Jim Woolsey, "Of all the threats that could inflict major damage to the U.S., terrorists using weapons of mass destruction is the threat for which the nation is least prepared." The study group notes that although existing capabilities work well for planned high-risk events like the 1996 Atlanta Olympics, no integrated system is in place to deal with a threat of the magnitude, complexity, and severity of WMD terrorism.

The study group recognized that a nascent national policy addressing the threat of WMD terrorism is in place, that it is being implemented at the level of the National Security Council (NSC) by a small staff, and that this high-level

Table 1. End-to-end strategy for responding to threats and acts of WMD terrorism.

Intelligence and warning	Prevention	Crisis management	Consequence management	Retaliation
• Strategic warning • Tactical warning	• Denial • Demotivation • Deterrence • Elimination	• Detection • Threat validation • Location • Weapon assessment • Impact assessment • Attribution • Demotivation and deterrence • Render safe	• Damage assessment • Evacuation and protection • Reconstitution • Cleanup	• Attribution • Prosecution • Military response

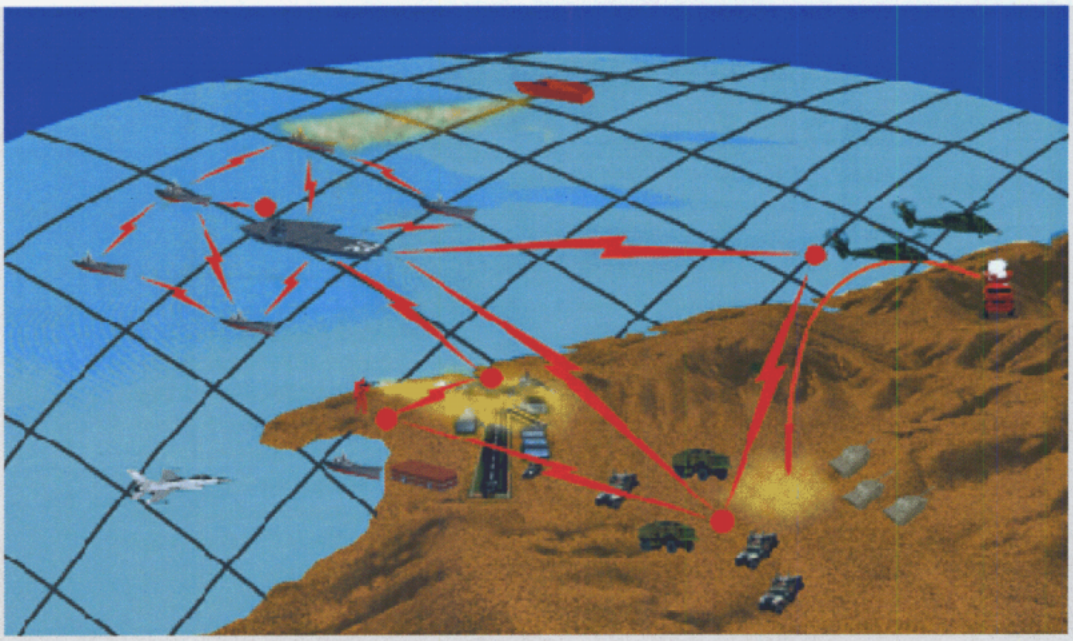

Figure 1. The Joint Biological Remote Early Warning System (JBREWS) is a system of networked sensors and communication links being developed to rapidly alert field troops of an attack with biological weapons.

group's efforts are making progress in coordinating national resources to meet the challenges posed by WMD terrorism. However, much remains to be done.

National Strategy Recommended

The study group's overriding recommendation is, therefore, to give the threat of terrorism using WMD the highest priority in U.S. national security policy. Specifically, it recommends an accelerated and intensified national program, integrated across the entire federal system and managed as a program out of the NSC, to address comprehensively the threat of WMD terrorism.

The study group emphasized that an end-to-end systematic strategy is the best defense against WMD terrorism. Through an enhanced national program, an end-to-end systematic strategy could be implemented that integrates technology, operations, and policy and provides a framework for coordinated local, state, and federal emergency response. "We are not alone in our thinking," says Wayne Shotts, Laboratory Associate Director for Nonproliferation, Arms Control, and International Security and study sponsor. "A number of other studies related to the WMD threat have echoed the recommendation for a more robust national program." The Livermore Study Group takes these recommendations several steps further, urging an end-to-end strategy to provide a multilayered defense—from detection and prevention to reversal and response—in which all phases of a potential WMD terrorist attack can be addressed (Table 1).

Regarding the need for enhanced capabilities, the study group recognizes that many of the agencies responsible for counterterrorism have initiated significant new efforts to enhance U.S. capabilities in this arena. Nevertheless, in looking at an end-to-end strategy, the group identified a number of promising activities to improve the nation's ability to counter the threat of WMD terrorism.

For example, in the area of intelligence and warning, the study group's key recommendations are for more and better technologies and systems for tracking materials and activities indicative of WMD development, production, or transport and for policies and approaches that allow U.S. law enforcement agencies to function effectively in the modern communications-technology environment.

For the prevention phase, the study group calls for additional exploitation of diplomatic efforts, foreign policy, and treaties to promote WMD nonproliferation, strengthen international law enforcement, counter the conditions that foster terrorism, and facilitate the use of technology to counter WMD terrorism. They also note the need for better material control programs worldwide to prevent weapons materials from reaching the hands of terrorists and for expanded border protection programs to detect and intercept WMD materials.

To improve U.S. capabilities in crisis management, the study group urges accelerated development of new sensor systems (or improvement of existing systems) for detecting, identifying, and locating WMD materials and devices as well as technical capabilities for disabling and rendering WMD devices safe. Also required for more effective response and deterrence are better technologies, databases, and other means of forensic identification and attribution of the source, origin, and pathways of weapon materials and devices.

For consequence management, the study group stresses the need for intensified planning and preparation to enable emergency response personnel and medical communities to deal with mass casualties caused by WMD agents. The group also calls for faster and more accurate atmospheric transport and deposition models for determining the populations at risk if biological or chemical agents are released.

"The study group recognizes that implementing an integrated national program to deal with the constantly

changing threat of WMD terrorism will not be simple or straightforward," says Joe Nye, study co-chair. "However, we must not wait until a disaster of Pearl Harbor proportions forces us to recognize the severity of this threat and the need to mount an adequate defense."

Strategic Support from New Technologies

While the study group's charter does not extend beyond analysis and recommendations regarding WMD terrorism, Dennis Imbro, a Livermore scientist who served as liaison to the group, notes that "there must be a marriage of technology and policy to effectively counter this threat." The national laboratories are a valuable source of innovative and advanced technologies and thus can make important contributions to this critical aspect of national security. A number of technologies are being developed or refined at Lawrence Livermore that can address gaps in current U.S. counterterrorism capabilities.

One particularly promising technology with anti-WMD-terrorism application is the Wide-Area Tracking System (WATS) for detecting and tracking a ground-delivered nuclear device. Another is the Joint Biological Remote Early Warning System (JBREWS) for alerting U.S. field troops of an attack with biological agents (Figure 1). Both systems consist of a network of sensors and communications links, with information continuously evaluated by unique data-fusion algorithms. The sensors can be permanently deployed at chosen locations or mounted in vans for deployment on demand to protect specific areas for specific situations or events.

A portable radiation detector developed at Livermore to monitor and detect nuclear materials in the field at ambient temperatures also has potential uses to defend against WMD terrorism (Figure 2). The new system is based on a relatively new cadmium–zinc–telluride detector material and can separate gamma- or x-radiation energies to identify the isotopic signature of nuclear materials such as plutonium and uranium. The system has immediate applications, for example, in detecting and deterring nuclear smuggling through airports and shipping ports and in national and international nuclear materials safeguard operations.

To detect biological weapons, Livermore has developed immunoassay and DNA recognition-based sensors. Unlike most biodetection instruments, which are bulky and can only be used in laboratory settings, the mini-flow cytometer and the mini-PCR (polymerase chain reaction) instrument can be used in the field to identify specific biological warfare agents. (See *S&TR*, July/August 1997, pp. 14–16.) Both have been tested successfully at the U.S. Army's Dugway Proving Ground in Utah.

Livermore is also home to the Forensic Science Center, which uses a wide range of advanced chemical, biological, and nuclear analysis techniques to examine samples for the U.S. government and law enforcement agencies. Forensic science techniques are essential for identifying the source of WMD.

These Laboratory technologies and capabilities and others like them contribute greatly to meeting the monumental challenge of countering the threat posed by WMD terrorism.

—Lauren de Vore

Figure 2. The portable radiation detector being demonstrated by its inventor Anthony Lavietes can identify the precise isotopic signature of nuclear materials such as plutonium and uranium by detecting gamma radiation. It improves upon the large germanium-based detectors shown in the background and has a variety of applications, among them assistance with defense against terrorism using weapons of mass destruction.

Key Words: counterterrorism, cytometer, Forensic Science Center, Joint Biological Remote Early Warning System (JBREWS), Livermore Study Group, polymerase chain reaction (PCR) instrument, portable radiation detector, weapons of mass destruction (WMD), Wide-Area Tracking System (WATS).

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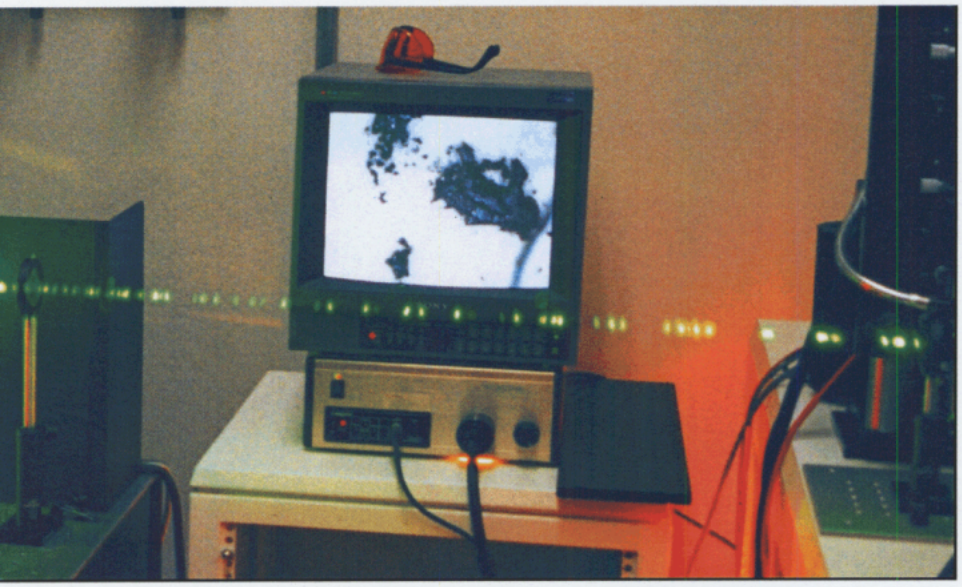

The photo above shows the imaging laser-ablation mass spectrometer system in action. From the left, the 2.5-gigawatt-per-cm² Nd:YAG (neodymium yittrium-aluminum-garnet) laser beam is passing through steering and alignment optics in the imaging system and into the mass spectrometer. A display of the target material is visible on the videoscreen. To the left is a magnified human hair after bombardment by the laser beam.

example, ingestion of or exposure to certain chemicals, including illegal drugs, can be identified in human hair. Since human hair generally grows at about one-half inch per month, analysis of a person's hair along its length can provide a chronology of drug use over time (see photos above). Or the hair of a dog known to have been kept as a pet at a suspected drug manufacturing facility can be analyzed to determine chemicals associated with chemical spills and exposures at the drug lab. Positive identification of chemicals in the dog's hair, indicative of the lab's operations, could serve as criminal evidence in a trial.

Although this technique is still in its infancy, its potential could be enormous. As lasers become easier to use, smaller and smaller particles and fibers will be sampled and characterized in forensic investigations.

Miniaturizing the GC/MS

The Forensic Science Center is also at the forefront in developing new, portable systems capable of real-time analysis in the field. These units have numerous applications, from identifying materials to support verification of the Chemical Weapons Convention to investigating criminal activities.

Almost five years ago, the Center developed a suitcase-size gas chromatograph/mass spectrometer (GC/MS) for on-site identification of ultratrace (microgram or less) quantities of certain compounds in complex mixtures. The system weighed 68 kg (150 lb), which made it portable, but only barely. Three years later, the system's weight had been cut by more than half to 32 kg (70 lb), still a hefty load. Today, at 20 kg (44 lb), with an accompanying laptop computer, this system can realistically be considered portable. This rugged, all-metal vacuum vessel can be carried on board an airplane and put into the overhead compartment, while its accompanying generator and off-line vacuum reconditioning pumping unit travel in the baggage compartment.

Reduction in size does not mean a reduction in performance. The latest complete GC/MS unit is able to achieve the almost-perfect vacuum required for accurate analysis. It can run for 12 hours in the field, and, like a 500-lb bench-top model, can perform up to 200 operator-assisted analyses per day. While the operator sleeps, the

All of the traveling components of LLNL's miniaturized gas chromatograph/mass spectrometer can fit into a metal travel case. Included are (on table) the GC/MS and laptop computer and (on floor) the pumping unit and generator.

turbomolecular pumping station refreshes the vacuum and other systems in the unit for another 12 hours of operation.

And how have they made this unit so small? When LLNL first took on the job of making a portable GC/MS system, very few off-the-shelf parts were available that, when assembled, would fit into anything the size of a suitcase. Almost all of the pieces that went into the first 68-kg unit were therefore designed and manufactured at LLNL. Meanwhile, miniaturization began to catch on in the GC/MS industry, so many of the components of the 32-kg version could be purchased from outside sources. While a few components of the latest 20-kg model had to be produced here, most have been purchased commercially, modified as necessary, and fitted together.

The unit's hydrogen supply for the portable gas chromatograph is typical of the shrinking components. The hydrogen supply in the 68-kg model weighed 14 kg. Today it weighs just 0.4 kg and still operates at 250 psi, just like its bigger bench-top brother.

The Center also has produced another unit whose parts can be replaced in the field. Parts are fitted together with O-rings, which facilitates repair, but more pumping capacity is needed to hold the desired vacuum. So there is still much work to do.

Counter-Forensic Inspection

In the summer of 1994, DOE asked the Forensic Science Center to perform a preliminary "counter-forensic" analysis to help the government investigate vulnerabilities of two gaseous-diffusion, uranium-enrichment plants that will be subject to international inspections. Although inspections of the plants are expected to be visual only, DOE wanted to know whether a hypothetical inspector with a different agenda, while walking through one of its plants, could surreptitiously collect samples of material, take them home, examine them, and replicate the enrichment process. The Center's mission was to examine the similar samples and learn critical details of the enrichment process.

In the gaseous diffusion enrichment process, uranium hexafluoride passes through a series of semipermeable barriers, the number of barriers being determined by the enrichment required. Uranium used in power reactors requires less enrichment than weapons-grade uranium, which is highly enriched.

The Center used for its analysis a variety of materials collected from different areas in the plant. With minute quantities of these materials and state-of-the-art analytical equipment, our chemists, engineers, and metallurgists were able to determine whether or not various aspects of the enrichment process are vulnerable to surreptitious collections. We expect these results to be useful in determining future inspection protocols.

[redacted] ***For further information contact Brian Andresen (510) 422-0903 (andresen1@llnl.gov).***

Forensic Science Sleuthing

LIKE high-tech colleagues of Sherlock Holmes, experts from Lawrence Livermore's Forensic Science Center develop sophisticated analytical equipment for combatting terrorism and the proliferation of weapons of mass destruction, supporting stockpile stewardship efforts, and responding to law-enforcement requests. Using center-developed prototypes, these experts in organic, inorganic, biological, and nuclear chemistry can determine the composition and often the source of the most minute samples of evidence. The sophistication of their sleuthing is beyond the wildest dreams of even Mr. Holmes and Dr. Watson.

Past issues of this publication have detailed the techniques of the center (*E&TR*, March 1994, pp. 1–8; and *S&TR*, August 1995, pp. 24–26). Some of the systems and methods have now "come of age" and are used in the field for remote analyses and real-time results.

This summer in Cape Cod, Massachusetts, the center first used its portable thin-layer chromatography system in the field for the first time. This system interrogated the interior of more than a thousand munitions dating back to World War II. The center also placed modern solid-phase microextraction (SPME) sampling tools at a Department of Energy weapons plant to monitor the safety and efficacy of the current nuclear stockpile. In the law-enforcement arena, the center is a key participant in the new partnership between the Federal Bureau of Investigation (FBI) and Lawrence Livermore (see the box on p. 84).

Blast from the Past

During an environmental cleanup operation at the Massachusetts Military Reservation in the spring of 1998, Army personnel discovered a suspicious depression in an area once used for training. The depression turned out to be the "burial ground" for mortars and ordnance that had been used during target practice exercises (Figure 1). Three questions needed answers: How many of the munitions were "live"? How should they be rendered safe? What was the best way to dispose of them?

Brian Andresen, director of the Laboratory's Forensic Science Center, assessed the situation at the request of the Defense Ammunition Center. His initial samples indicated that approximately one munition out of ten was live, while the rest were dummies of wax and plaster of paris. Although they couldn't explode, the dummies did have live fuses, and some of the rounds—the exact quantity unknown at that point—could have contained appreciable quantities of high explosive (HE).

Figure 1. When the Army unearthed more than a thousand mortar rounds dating from a World War II training area, they enlisted the Laboratory's Forensic Science Center to determine which were live munitions and which were dummies.

Andresen recommended cutting each of the thousand-plus mortars in half and sampling them for HE. The Army agreed, so in July 1998 Livermore's Jeff Haas and Greg Klunder packed up sampling kits and analysis equipment and headed east.

The project was an ideal test case for the center's thin-layer chromatography (TLC) screening system, which was originally developed as a field-portable propellant analysis system for the Department of Defense. Propellants (essentially HE) require stabilizers (such as diphenylamine) to prevent spontaneous ignition. Because stabilizers are depleted by extended exposures to high temperatures, the military needed a way to quickly determine the safety of large numbers of bulk propellants. The TLC system screened the Army site for explosive compounds. Sensitive and fast, the system required only 50-milligram samples of explosive, instead of the gram quantities required by other methods, and 15 minutes for each group of 20 samples.

Haas and Klunder analyzed 1,236 mortar rounds in two days (Figure 2). With the real and dummy munitions identified, the Army sent the dummy pieces to a military salvage yard and safely disposed of the remaining live shells. In the past, normal protocol was to group the mortars—live ones and dummies together—in piles of 100 and to explode them all, but that solution is no longer considered environmentally acceptable.

The nearby town of Borne also gained peace of mind from the center's analysis. The work demonstrated that the HE

amounts were insignificant and that environmental contamination did not occur while the munitions were buried.

Back to the Future for the Stockpile

In 1998, center staff also developed methods for verifying the safety of the weapons systems in the U.S. nuclear stockpile.

"Our task was to provide a way of determining the condition of a nuclear weapon's internal components without using either electricity or light and without disturbing the weapon's internal geometry," said Andresen.

The materials in a modern nuclear weapon include highly sensitive and reactive components, such as plutonium and uranium, as well as organic materials. These organic materials include the HE that initiates the nuclear fission reaction as well as structural materials and adhesives that maintain precise internal alignments. Such materials are stable polymers with small diffusion coefficients (10^{-11} to 10^{-5} square centimeters per second). However, in the weapon environment—over a period of many years, at elevated temperatures, in a hermetically sealed radioactive environment—certain systems may outgas at detectable levels. When outgassing, these organic materials release compounds that can indicate problems such as corroded metals, degrade components that affect the overall integrity of other warhead materials, and generally signal decomposition of materials within the warhead. By monitoring these chemicals, experts are alerted to problems that may be developing inside the weapon.

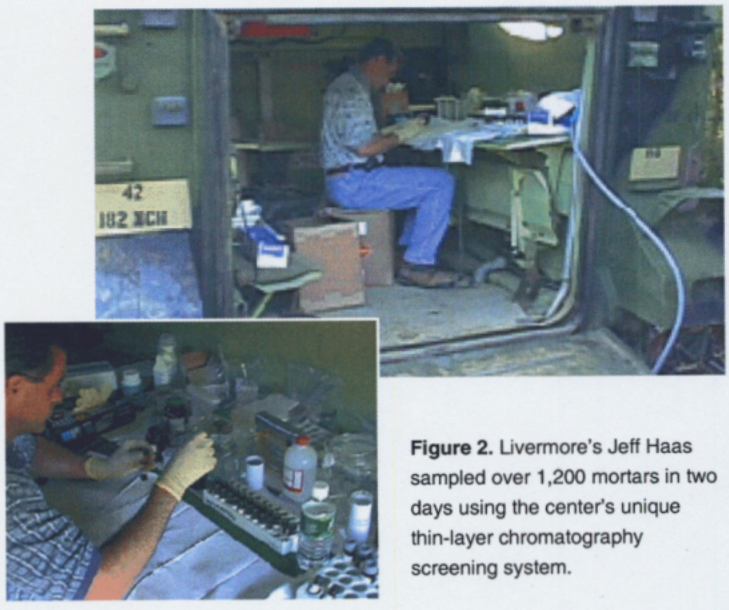

Figure 2. Livermore's Jeff Haas sampled over 1,200 mortars in two days using the center's unique thin-layer chromatography screening system.

Recipe for Safety: Yellow Cake and Simple Green

In the summer of 1998, Secretary of Energy Bill Richardson announced a new partnership between the Federal Bureau of Investigation (FBI) and Lawrence Livermore to combat international terrorism with high technology. This formal partnership affirms the role the Forensic Science Center plays in supporting forensic investigations.

Two recent incidents—both with happy endings—demonstrate the speed and efficiency with which the center responds to urgent requests from law-enforcement agencies and nuclear regulators.

The first incident involved unknown material in a coffee can obtained by a high school student at a local swap meet. The material—a light yellow, very fine powder—was confiscated by the school. The material was discovered to be radioactive, and the center was called in by DOE.

Nuclear chemist Ken Moody performed the analysis and relayed the results back to DOE within 16 hours of receiving the material. "Since everyone was anxious to get immediate results, we expedited nuclear counting techniques and assayed the material with gamma-ray spectrometry and alpha-particle spectroscopy. We measured no radionuclides above background other than unperturbed isotopes of uranium. The material was naturally occurring uranium, or yellow cake, not an enriched or otherwise processed uranium compound."

The second incident occurred as FBI agents searched the Los Angeles home of a man arrested for stealing military weapons. Among an arsenal of assault rifles, hand guns, explosives, and heavy-duty flak vests, they found a jar of green liquid labeled "poison." Concerned that the liquid might be a chemical warfare agent, the FBI contacted the center.

"Rich Whipple and I conducted field sampling within an FBI-controlled area," explained Pat Grant, deputy director of the center. "We put the sample—which had been well packaged by a hazardous materials team—into a containment glovebag inside a field-portable hood. Using the solid-phase microextraction (SPME) technique, we exposed two microfibers, one at a time, to the liquid and then repackaged the jar. We transported the SPME fibers to the center in O-ring-sealed metal containers. Armando Alcaraz performed gas chromatography–mass spectrometry (GC–MS) analyses, we analyzed and interpreted the data, and the results were reported to the FBI just two-and-a-half hours after the start of our investigation."

Good news. The green substance turned out to be a nontoxic cleaning solution. In fact, the next day Whipple brought in a commercial "simple green" household cleanser and ran a SPME GC–MS analysis of the fluid. The chemical signatures of the commercial product and the suspect solution were virtually identical.

The techniques and analytic protocols rely on center-developed solid-phase microextraction (SPME), which allows rapid and efficient environmental sampling and processing. The key to microextraction is a minuscule fiber inside a syringe needle (Figure 3). The fiber is coated with an adsorbant that, when exposed to the ambient environment, collects the molecules of a suitable sample.

Five types of fiber with specialty polymer coatings are available commercially. For example, one fiber picks up acids in preference to bases; another extracts alcohol more efficiently than hydrocarbons. Each SPME fiber coating can collect thousands of different compounds of a specific class after only a few seconds of sampling time. Before the development of this technique, it took weeks to collect and characterize only a few tens of unknown compounds from warhead materials.

In the SPME project, chemists David Chambers and Heather King are identifying the gas-phase chemicals in a weapon's primary headspace and studying their time histories. "In the first phase of this project, we're identifying what chemicals, if any, are emitted by weapon components," said Chambers, the project's principal investigator. "So far, we've characterized weapons-material components as well as HE associated with two weapons systems."

The most recent stockpile stewardship application of the SPME technique involves monitoring the headspace of individual warheads. For instance, at the Pantex Plant in Amarillo, Texas, SPME is being used with other types of nondestructive surveillance to monitor 10 weapons.

The Future of Forensic Analysis

The term "forensic science" used to apply only to the scientific analysis of evidence in the context of civil or criminal law. Increasingly, forensic analyses are used to monitor or verify compliance with international treaties and agreements—particularly those involving weapons of mass destruction—and for stockpile stewardship.

A busy future of forensic science was recently underscored by DOE Secretary Bill Richardson in his August 1998 visit to Lawrence Livermore, when he announced that the Laboratory was the first in a "network of premier laboratories around the country that will give the FBI next-generation crime-fighting capacity."

Holmes and Watson would be proud!

— Ann Parker

Key Words: Federal Bureau of Investigation (FBI), Forensic Science Center, gas chromatograph–mass spectrometer (GC–MS), solid-phase microextraction (SPME), thin-layer chromatography (TLC).

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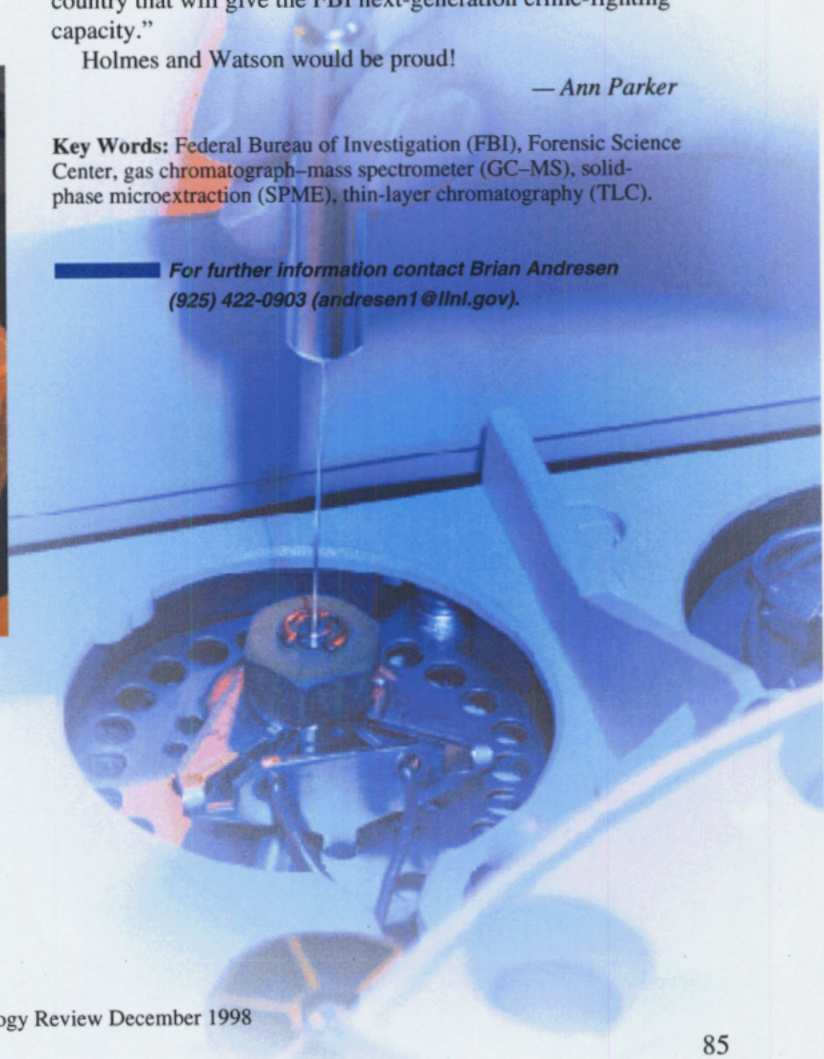


Figure 3. (above) Heather King and David Chambers demonstrate Livermore's solid-phase microextraction (SPME) sampling technique. The microfiber inside the syringe is coated with a special polymer that collects molecules of gas-phase chemicals. (right) The fiber is then desorbed in the injection port of a gas chromatograph–mass spectrometer, which identifies the compounds and measures their amounts.

Seismic Monitoring Techniques Put to a Test

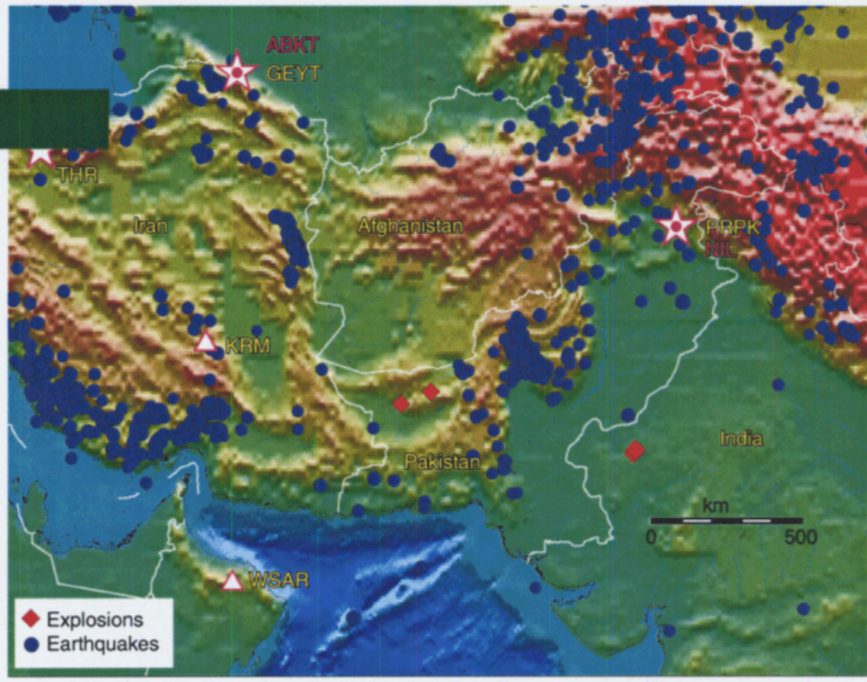


Figure 1. Topographic map showing the locations of the Indian nuclear tests in 1974 and on May 11 and 13, 1998, the Pakistani nuclear tests on May 28 and 30, 1998, and earthquakes recorded in the region between 1995 and 1997. Also shown are the planned locations of the International Monitoring System's primary (stars) and auxiliary (triangles) seismic stations and the Incorporated Research Institutions for Seismology's stations closely collocated at Alibek, Turkmenistan (ABKT), and Nilore, Pakistan (NIL).

WHEN the world received the news of the Indian and Pakistani clandestine underground nuclear tests last May, a team of Livermore researchers used the events to validate several seismic methods they have developed over the past decade to monitor the Comprehensive Test Ban Treaty (CTBT). Using data recorded worldwide by a host of seismic monitoring stations, the team successfully differentiated the nuclear blasts from typical regional earthquakes, characterized the yields of the tests, and noted inconsistencies between the announced test yields and the seismic data. In all, the seismic signals from the nuclear tests provided important new data to help calibrate seismic stations in a critically important region of the world.

The CTBT has been signed by 152 nations, although not by India or Pakistan. The treaty provides for an International Monitoring System (IMS) of automated seismic stations, many of them still to be installed, to record any evidence of clandestine nuclear explosions. These stations transmit data via satellite to the International Data Center in Vienna, Austria, which in turn distributes them to national data centers around the world. Figure 1 shows the location of existing seismic stations in the Southwest Asia area, planned IMS seismic stations, the seismically determined locations of the recent tests by India and Pakistan, and locations of some recent earthquakes in the region.

The U.S. Department of Energy is supporting the U.S. National Data Center (USNDC) at Patrick Air Force Base, Florida, as it prepares to monitor the treaty. As part of DOE's effort, teams at Livermore and Los Alamost have been working to improve ways to seismically characterize clandestine underground nuclear explosions and differentiate them from other sources of seismicity, such as earthquakes and mining explosions. Much of Livermore's work has centered on developing regional discriminants, which are characteristic features of a seismic waveform (for example, the peak amplitude at a particular frequency, within a specific time frame) recorded at distances less than 2,000 kilometers away. These discriminants are used to differentiate between explosions and other types of seismic sources. (See the September 1998 *Science & Technology Review*, "Forensic Seismology Supports the Comprehensive Test Ban Treaty," pp. 4–11.)

India's nuclear test took place on May 11 and 13, 1998, followed by Pakistan's on May 28 and 30, 1998. None of the planned IMS seismic stations in the region was installed at the time of the tests. Fortunately, stations belonging to IRIS (Incorporated Research Institutions for Seismology), a consortium of U.S. universities, were operating. Two of those stations, called ABKT, in Alibek, Turkmenistan (one of the former Soviet republics), and NIL, in Nilore, Pakistan, were near the sites of two proposed IMS stations GEYT and PRPK. While ABKT data were not available, NIL records of the Indian tests, some 740 kilometers away, were available through the Internet within a few hours, as were data provided by IRIS for other stations throughout the world. The NIL station was turned off during the Pakistan tests, so the data were unavailable.

As part of their calibration work for the USNDC, the Livermore seismologists had already collected and analyzed data recorded by NIL and other seismic stations from more than 200 regional earthquakes between 1995 to 1997 in Iran, Afghanistan, Pakistan, western India, and the surrounding

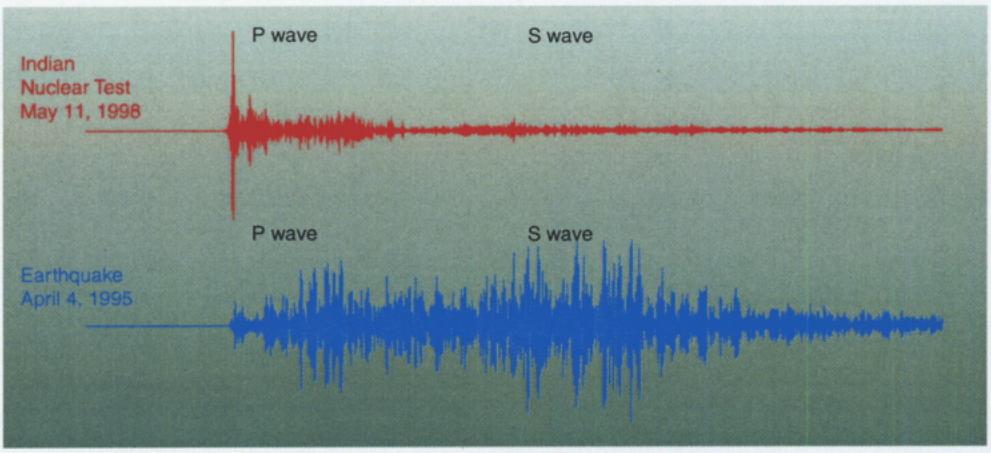


Figure 2. Seismograms of the Indian nuclear test (top) and a representative nearby earthquake (bottom) recorded at the seismic station at Nilore, Pakistan. These seismic signatures for an explosion and earthquake are typical and clearly distinguish one from the other.

region. Within hours of the announcement of the May 11, 1998, Indian tests, Livermore seismologists were comparing its seismogram with those from nearby earthquakes.

As seen in Figure 2, the seismogram from a representative earthquake clearly differs from that of the May 11 test. Livermore-refined discriminants based on P and S waves were strongly indicative of an explosion, not an earthquake or other seismic source, at all frequencies tested (0.5 to 8 hertz). Livermore seismologist Bill Walter explains that the differences in seismic P- and S-wave energy provide one method of discriminating explosions from earthquakes. Seismic P waves are compressional waves, similar to sound waves in the air. Shear (S) waves are transverse waves, like those that propagate along a rope when one end is shaken. Because underground explosions are spherically symmetric disturbances, they radiate seismic P waves efficiently. In contrast, earthquakes result from sliding or rupture along a buried fault surface and strongly excite the transverse motions of S waves. Thus, we expect that explosions will show strong P waves and weak S waves and that earthquakes will show weak P waves and strong S waves, as seen in Figure 2.

According to Walter, one way to quantify this difference is by determining the ratio of P-wave to S-wave energy measured from the seismograms. Explosions should have higher P/S ratios than earthquakes, but the frequency at which the best separation occurs varies by region and station. Figure 3 shows the P/S ratio for the May 11 Indian test and for earthquakes shown in Figure 1. The measurements in Figure 3 were made at four different frequencies. The Indian test has a higher P/S ratio than the earthquakes, as expected.

India reported that its nuclear testing on May 11, 1998, was composed of three almost simultaneous explosions with yields of 45, 15, and 0.2 kilotons and that the two larger tests were separated by about a kilometer. According to Walter, the team's examination of regional data recorded at NIL and at teleseismic stations thousands of kilometers away did not reveal obvious signs of multiple shots. The U.S. Geological Survey reported a teleseismic magnitude of mb 5.2 (mb is the bodywave magnitude and is roughly related to the Richter scale). Assuming simultaneous detonation of the three tests and using published magnitude–yield formulas for a stable region, the announced total yield of 55 to 60 kilotons appears to be at least three times larger than the yield indicated by the seismic data.

Livermore researchers then compared the seismogram from the May 11, 1998, tests with India's May 18, 1974, single test (its only previous nuclear test) using data from stations in Canada and Scotland that recorded both events. The 1974 test generated a clearly detected teleseismic signal with an mb of 4.9. Because India declared the 1974 explosion a "peaceful nuclear explosion," some information about it was reported, such as the fact that it was a single explosion at a depth of 107 meters. However, Indian scientists and officials stated a large range in the yield estimate—4 to 12 kilotons.

Figure 4 shows the seismograms from the 1974 and 1998 tests using data from the Canadian station (for ease of comparison, the 1974 test's amplitude is doubled to match that of the 1998 test.) The two seismic waveforms show remarkable similarity.

Several interpretations of the seismic observations are possible. According to Livermore seismologist Arthur Rodgers, if the three 1998 shots were indeed detonated nearly simultaneously and separated by less than a few kilometers, "We would probably see just one large shot in the seismic waves." Rodgers also says that the second and third shots could have been so small compared to the first that they were overwhelmed in the seismogram. Also, a cavity or substantial amount of porous material near the explosive site could, if present, have reduced the coupling of energy into seismic waves, thereby significantly reducing the seismic magnitude of all three tests. Finally, it is possible that the yield announced by the Indian scientists was simply three to six times too large.

On May 13, India announced two additional low-yield tests totaling 800 tons. The Livermore team examined data

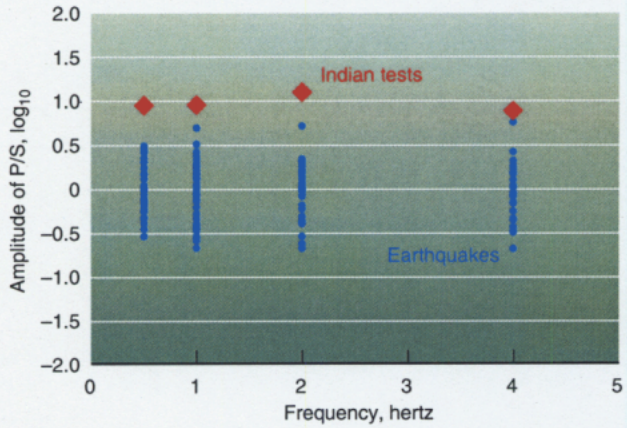


Figure 3. P-to-S amplitude ratios versus frequency for the Indian nuclear test (diamonds) and nearby earthquakes (circles). Note that the P- to S-wave ratios are higher for the Indian test than for the earthquakes.

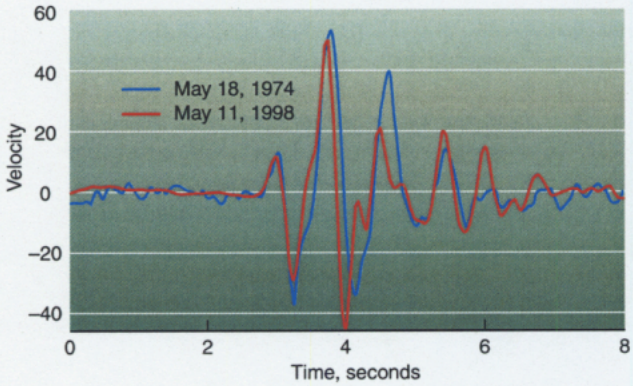


Figure 4. Signals from the 1974 and 1998 Indian underground nuclear tests recorded in northern Canada. (To make the similarities more apparent, the amplitude of the May 18, 1974, data has been doubled.)

provided by the NIL station, but none showed any obvious seismic signal. Using the largest amplitude of the background earth noise around the time of the test as an upper bound for the signals from the event, the Livermore researchers determined that the event must have produced an mb of less than 2.8. The two tests were said to be conducted in a sand dune, which might poorly couple the explosive energy into seismic waves and thus reduce the strength of any recorded seismic signal. Adjusting for this geologic condition, says Walter, a signal should have been observable at NIL if the yield was 100 tons or more.

Walter says that the nuclear tests in India provided valuable data in a region with only a single previous nuclear test. This data will be used to help calibrate the CTBT monitoring network.

The data from the Indian tests will also improve scientists' understanding of the physical basis of the regional discriminants developed at Livermore. As a result of the tests, the discriminants may be applied with greater confidence to much lower yield explosions than the Indian tests and in South Asia and other regions where no nuclear test data are available to calibrate nearby monitoring stations.

The Livermore team plans to conduct more research to further characterize the May events as additional seismic data and information on emplacement conditions become available from Indian and Pakistani officials and scientists. In the meantime, researchers are hopeful that their detailed analysis of the nuclear tests, done without the forthcoming IMS stations, shows that the planned international network will indeed be effective in detecting and identifying clandestine nuclear tests.

—Arnie Heller

Key Words: Comprehensive Test Ban Treaty (CTBT), discriminants, U. S. National Data Center (USNDC), nuclear test.

For further reading:

W. R. Walter, A. J. Rodgers, K. Mayeda, S. Myers, M. Pasyanos, and M. Denny, *Preliminary Regional Seismic Analysis of Nuclear Explosions and Earthquakes in Southwest Asia*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-130745, July 1998.

For further information contact Bill Walter (925) 423-8777 (bwalter@llnl.gov) or Arthur Rodgers (925) 423-5018 (rodgers7@llnl.gov). Information on DOE's overall CTBT program may be found at www.ctbt.rnd.doe.gov.

At the Crossroads of Technology and Policy

The Center for Global Security Research brings together policymakers and scientists to enhance national and world security.

WHEN Attorney General Janet Reno announced the establishment last February of a new FBI center to investigate and prevent attacks on the nation's critical infrastructure, she did not appear at Department of Justice headquarters in Washington, D.C. Instead, she chose to make her announcement at a Lawrence Livermore workshop co-sponsored by a small organization that is attracting increasing attention from top scientists and government policymakers worldwide.

That organization is Livermore's Center for Global Security Research (CGSR), established in 1996 to bring the technology and policy communities closer together. Its goal is to reduce threats to international security, especially those associated with weapons of mass destruction, by sponsoring workshops, research fellows, and independent analyses to study important national and world security issues involving policy and technology.

CGSR Director Ron Lehman says the Center's "product" is fresh insight into some of the most vexing national security issues. Lehman notes that the Center is not afraid of getting into sensitive areas, but he emphasizes the need for fellows and participants to be

fiercely independent in their work, intellectually rigorous, and dedicated to hearing from an uncommonly broad range of viewpoints and backgrounds.

February's critical infrastructure workshop, for example, co-sponsored by Stanford University's Center for International Security and Arms Control, brought together a wide range of representatives from business, government, and technology (see box, pp. 94–95). They addressed ways to protect the nation's banking, communication, computer, and power networks from a host of potential adversaries, ranging from state-sponsored foreign terrorists to youthful hackers.

The workshop was but one illustration of CGSR's practice of joining Livermore scientists and engineers with other technical experts, academics, policymakers, military leaders, and industry executives to address issues involving national security technology and policy. Past workshop topics have included chemical and biological weapons terrorism, nuclear materials smuggling, relations with Russian nuclear scientists, the future of nuclear forces, and environmental security.

Small Is Good

The CGSR is deliberately small; there are no permanent employees other than administrator Karen Kimball. Lehman and half-time special assistant Eileen Vergino, a seismologist, are on rotation while retaining other responsibilities at Livermore. The Center invites Livermore specialists and outside scientists to work together on specific tasks for a limited time, publish their findings, and then return to their main activities. "I think of us as a think tank constantly reorganizing itself as it takes on new tasks," Lehman says.

Lehman is the first to point out that the nation has no shortage of think tanks and national security study centers. The uniqueness of CGSR, however, derives from its close affiliation with Lawrence Livermore, one of the few U.S. institutions with expertise in all phases of nuclear weapons development. Lehman cites Livermore's strengths in analysis, modeling, and computer simulation as important resources that are regularly tapped for CGSR-sponsored research. The table on p. 92 summarizes the Center's multidisciplinary support from all Laboratory directorates.

While Lehman reports to Livermore Director Bruce Tarter, the CGSR is part of the Nonproliferation, Arms Control, and International Security (NAI) Directorate. The Center's activities complement the diverse efforts of NAI specialists to prevent the proliferation of weapons of mass destruction, assist in arms control matters, and build stronger relations with scientists of the newly independent states of the former Soviet Union.

As CGSR director, Lehman relies regularly on his diplomatic experience with and knowledge of arms control issues. Before joining Lawrence Livermore in 1993, he served as director of the U.S. Arms Control and Disarmament Agency, Assistant Secretary of Defense for International Security Policy, Deputy Assistant to the President for National Security Affairs, and U.S. Chief Negotiator for the Strategic Arms Reduction Treaty I.

Lehman also chairs the governing board of the International Science and

The critical infrastructure workshop at Lawrence Livermore in February 1998 featured a panel discussion on ways to protect the nation's critical banking, communications, computer, and power networks from a variety of terrorist attacks. Panelists were (left to right): George Spix of Microsoft; Scott Penberthy from IBM; Tom Marsh, chairman of the Commission on Critical Infrastructure Protection; former Secretary of Defense William Perry; Philip Bobbitt from the National Security Council; David Cooper, Lawrence Livermore's Associate Director for Computation and Chief Information Officer; Ron Lee, Department of Justice; and Anita Jones, a professor at the University of Virginia. (Above) Former Defense Secretary Perry makes a point during the panel discussion.

Ron Lehman, Director of the Center for Global Security Research, works with administrator Karen Kimball (right) and scientist Eileen Vergino to plan one of the Center's diverse national security activities.

Technology Center (ISTC). Established in 1994 and headquartered in Moscow, the ISTC is funded by several Western countries. It is working to prevent the dispersion of knowledge related to weapons of mass destruction by financing nonweapons projects that integrate weapons specialists from the newly indepentant states of the former Soviet Union into the international scientific community. Both Lehman and Vergino, a scientific advisor to the ISTC, travel regularly to Moscow for ISTC meetings. (For more on the ISTC, see the September 1997 *S&TR*, pp. 19–20.)

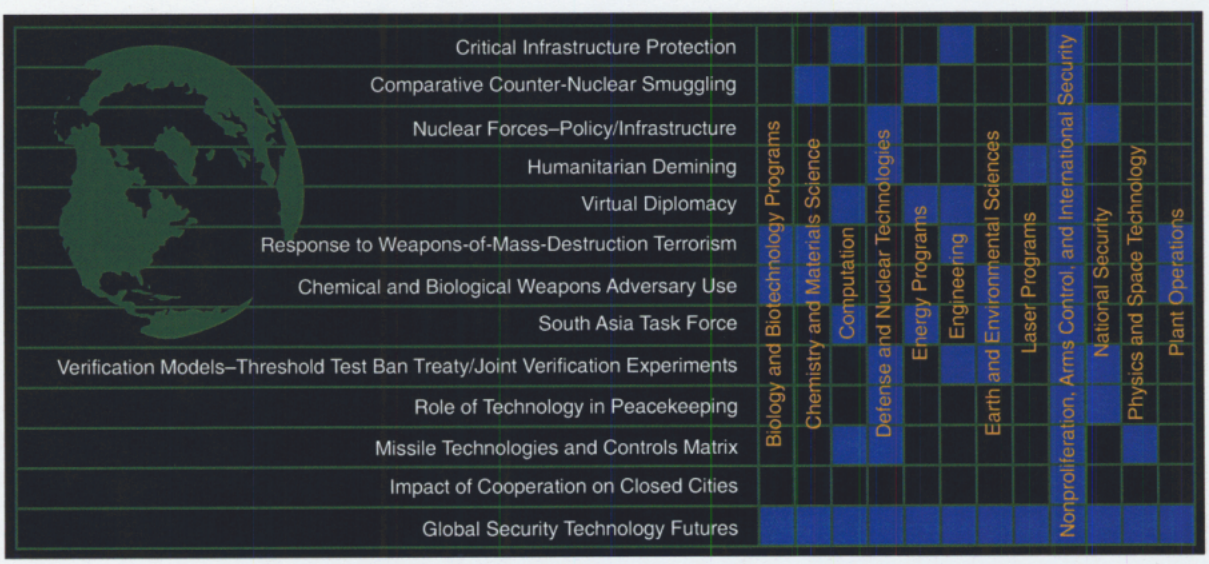
An International Perspective

The CGSR's international viewpoint is evident in its workshops, such as a seismic forum held last year involving Jordanian and Israeli scientists. Indeed, the Center's inaugural conference, "Meeting the Challenges of International Peace Operations: Assessing the Contributions of Technology," established a precedent when it attracted United Nations field commanders from around the globe to Livermore.

Former NAI Associate Director Bob Andrews led the effort to create the CGSR. At its inauguration, Andrews said, "Although the Laboratory has been a key player in providing technology support to U.S. and international agencies, we have not been as well connected to the policy community as we might. . . . Even the most clever and sophisticated technology must be assessed in terms of the overall policy framework, including options that it may or may not make available."

Those associated with CGSR activities hail its value as an educational and networking resource for both Livermore scientists and national policymakers. "We want to bridge the gap between the technology and policy communities," Lehman explains.

Livermore physicist Don Prosnitz, chief NAI scientist, is involving more NAI employees in CGSR activities because the interchange between technologists and policymakers is so valuable. "We want to get technologists into policy forums so that they understand the policy influences of the technology they're developing. We also

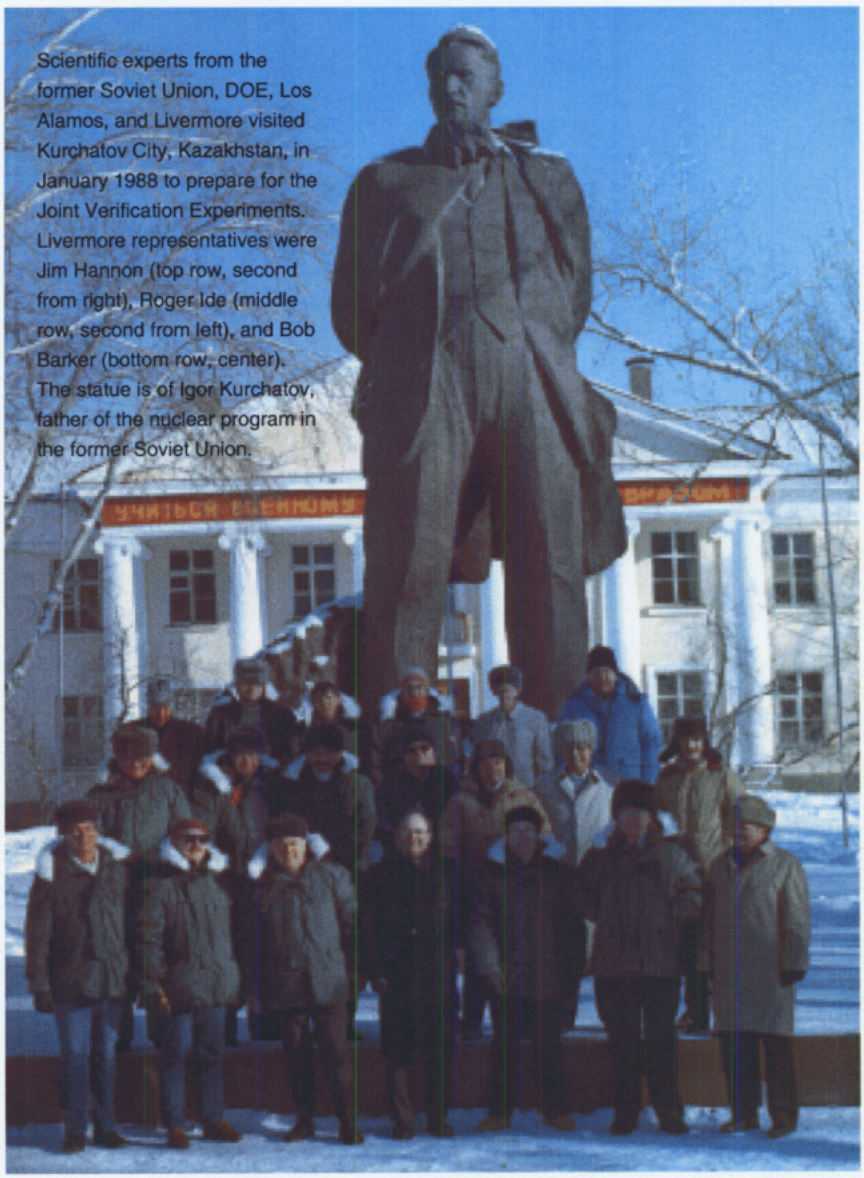


The Center for Global Security Research taps into expertise from across the Laboratory.

want to expose policy types to technologists so that they understand the limitations of technology."

Lehman notes that having an international perspective encourages examination of the cross-cultural aspects of security issues—with often surprising results. A 1997 workshop on protecting fissile materials, co-hosted by CGSR, Stanford University's Center for International Security and Arms Control, and the Monterey Institute of International Studies, revealed striking cultural differences. After workshop participants heard some experts explain the need for shock troops and air defenses to protect fissile-material storage centers, a Japanese representative noted that in his country, armed guards had long been disdained because once someone in Japan trusts another, it is considered very impolite (and a violation of that trust) to verify. Meanwhile, a South Asian speaker cited a similar cultural problem when guards of one social class must, as a part of their jobs, search the briefcases of scientists and officials of higher social classes.

Livermore chemist Jeff Richardson, principal deputy program leader in NAI, helped organize two workshops on fissile materials smuggling with the U.S. Air Force Institute for National Security Studies. Characteristic of CGSR activities, attendees represented major federal agencies, U.S. study centers, and representatives from France, Poland, Kazakhstan, Russia, the London Metropolitan Police, and even the Public Broadcasting System. "The Center provides the right forum for these kinds of interchanges," says Richardson. "It is an excellent opportunity to facilitate interactions on a global scale."



Scientific experts from the former Soviet Union, DOE, Los Alamos, and Livermore visited Kurchatov City, Kazakhstan, in January 1988 to prepare for the Joint Verification Experiments. Livermore representatives were Jim Hannon (top row, second from right), Roger Ide (middle row, second from left), and Bob Barker (bottom row, center). The statue is of Igor Kurchatov, father of the nuclear program in the former Soviet Union.

Case Study of the TTBT

This year, the CGSR began a case study in verification methodology by reviewing the events leading to the signing of the Threshold Test Ban Treaty (TTBT), which limited underground nuclear tests to 150 kilotons. Although negotiated in 1974, the treaty was ratified by the U.S. Senate in 1990 only after the establishment of a strict verification protocol with the Soviet Union. That protocol included the historic Joint Verification Experiments (JVE), whereby Soviet and U.S. teams for the first time conducted on-site yield measurements at each other's nuclear test sites.

"There is a tremendous richness of ideas and history associated with the TTBT," says Lehman. "It seemed useful to do a case study and look at the evolution of our thinking regarding the treaty and the meaning of 'adequate and effective' verification."

Vergino, who provided technical support to the U.S. delegates in Geneva during the treaty's protracted negotiations, is leading the study. She is being assisted by many of the principals involved in the treaty process, including specialists from Lawrence Livermore, Los Alamos National Laboratory, the Department of Energy, and the State Department.

"We believe our study may provide lessons for the future," says Vergino. "JVE was a turning point in Soviet relations with the West. Many American–Russian friendships were forged, and the more open atmosphere anticipated the post-Cold War era." She also notes that Livermore played a leading role in organizing the "Lab-to-Lab" interactions with the Russian nuclear institutes in the formerly closed Russian cities during that time. That relationship has expanded to include the exchange of electronic mail between Russian schoolchildren living in those cities and Livermore children in a program Vergino helped establish. (For other details on the Lab-to-Lab program, see the September 1997 *S&TR*, pp. 18–19.)

Vergino is hopeful that the Center's TTBT study will be ready in time to share with Russian colleagues at a 10-year JVE jubilee celebration being planned for this summer in Kazakhstan as well as at a technical exchange meeting also planned for this summer in Nevada. The CGSR is helping to coordinate American participation in the jubilee.

Another arms agreement receiving particular CGSR attention is the Convention on the Prohibition on the Development, Production, and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on their Destruction. Prosnitz has worked with the Center on three meetings devoted to various aspects of the treaty. "It's a very important treaty because it bans an entire class of

Preventing Attacks on the Nation's Critical Infrastructures

How vulnerable to cyber and physical attack are the nation's emergency services and telecommunications, electrical power, gas and oil storage, banking and finance, transportation, and water supply systems? In July 1996, President Clinton established the Commission on Critical Infrastructure Protection to assess the vulnerabilities and recommend ways of protecting these essential resources.

To examine many of the issues connected with the Commission's work, Lawrence Livermore's Center for Global Security Research (CGSR) and Stanford University's Center for International Security and Arms Control conducted two workshops at Stanford in March and July 1997. The workshops were attended by top-level representatives from government, industry, and academia. Participants also included Commission members and staff, who told CGSR Director Ron Lehman that they found the workshops invaluable in the preparation of their October 1997 final report.

Livermore senior engineer Stan Trost was instrumental in working with the two centers to sponsor the series. "If critical infrastructures like the Internet and phone system go down, the country is in trouble," says Trost. "We wanted a 'safe' place for participants, especially corporate and government representatives, to discuss their common concerns."

The Commission's final report identified significant vulnerabilities in the nation's critical infrastructures. It recommended an effort to educate the American public and industry; a broad program of cooperation and information sharing between government and industry; reconsideration of laws related to infrastructure protection; the strengthening of research and development; and the establishment of a national organization dedicated to all aspects of critical infrastructure protection.

Attorney General Janet Reno announces the formation of the National Infrastructure Protection Center during her visit to the Laboratory in late February 1998.

Implementing Recommendations

According to Lehman, the present task is to determine the best ways to implement the commission's recommendations. That was the focus of the series' third workshop, held at Lawrence Livermore on February 26 and 27, 1998. Workshop participants included William J. Perry, former Secretary of Defense; Tom Marsh, Commission Chairman; Michael May, co-director of Stanford University's Center

weapons, but it has no teeth," he says. One workshop focused on ways to strengthen inspection protocols with on-site biological sampling, while another explored ways for nations to cooperate if terrorists ever used biological weapons.

The CGSR invites Laboratory scientists—and those at other institutions—to apply for fellowships to pursue original research in one of four focus areas: management, control, and reduction of threats associated with weapons of mass destruction; security implications of emerging technologies such as biological and chemical weapons; threat anticipation and management; and the future role of military forces. A review committee recommends proposals for funding.

"We want research topics that leverage the talents and resources at LLNL," says Lehman. Visiting fellows are especially encouraged to seek broad interaction with Livermore employees. For example, Ken Weiss, formerly of the Arms Control and Disarmament Agency, is working with NAI specialists on issues concerning missile technology control. Previously, Jim Walsh from the Massachusetts Institute of Technology examined why fewer nations than originally predicted had acquired nuclear weapons.

Ridding the World of Mines

From within the Laboratory, physicist David Eimerl of the Laser Programs Directorate is doing a systems analysis of humanitarian demining as a half-time Center fellow. Recently, Eimerl chaired a CGSR-sponsored conference on technological solutions for clearing land mines. "There is a lack of coordination between the people who are on the front lines and those who are in labs developing the technologies. The workshop was a great way to get us educated."

He notes that the technological requirements posed by demining are

for International Security and Arms Control; Bruce Tarter, Lawrence Livermore Director; David Cooper, Livermore Associate Director for Computation; and representatives from RAND Corp., the White House Office of Science and Technology Policy, Cisco Systems Inc., Microsoft, Stanford University, University of Virginia, Blue Shield, the National Security Council, DOE's Office of Nonproliferation and National Security, the Department of Energy, the Department of Defense, SRI International, Sandia National Laboratories, U.S. Telephone Association, and others.

In her keynote address televised to Livermore employees, Reno warned that the nation's critical infrastructures have become "more vulnerable than ever before as we come to rely on technology as never before." As a result, she said, "I think this is the most extraordinarily challenging time that law enforcement has ever faced."

Reno said some of today's criminals "don't have guns; they have computers, and they may have . . . weapons of mass destruction." She said that to appreciate the dimensions of the problem, one only has to realize that "someone could sit in a kitchen in St. Petersburg, Russia, and steal from a bank in New York."

She noted that the Livermore workshop could not be more timely because the Administration was, at that moment, engaged in determining how to implement the Commission's report. She underscored the importance of the Commission's recommendation of a broad national partnership to ensure the protection of critical networks and systems.

Partnerships Work

Such partnerships do work, Reno emphasized, pointing to a recent New York hacker case that teamed the FBI, the Secret Service, Nynex, Southwest Bell, other private companies, and several universities to identify and prosecute individuals who had hacked into a telecommunications network, a credit reporting company, and other systems.

To promote partnerships and strengthen existing resources, Reno announced the establishment of the FBI's National Infrastructure Protection Center to detect, prevent, and respond to cyber and physical attacks on the nation's critical infrastructure. The new organization, she said, will include representatives from federal agencies and the intelligence community. She expressed hope that the private sector would be an active participant in the new center as well.

The Attorney General said the federal government must also work with scientists as partners "to develop technologies and processes that enable us to obtain evidence in strict adherence to the fundamental protections guaranteed our citizens by the Constitution." She suggested that scientists may need to work together with Fourth Amendment (protection from unlawful search and seizure) experts.

In conclusion, Reno said her visit to Lawrence Livermore was "extraordinarily helpful" and had convinced her that "based on the example of what you do here, we can make a difference. . . . Thank you so very much for setting an example."

Lehman is hopeful that Lawrence Livermore will play a significant role in helping to implement the Commission's findings. For example, its expertise in computer simulation for computer security applications has drawn significant interest from workshop participants and Commission members.

particularly daunting. "Demining is not like prospecting for gold. If you find some gold, even if you don't find all of it, you're happy. But with demining, you have to find all the mines; you can't miss a single mine. Doing anything 100% is an incredible challenge."

Eimerl says that demining also involves fascinating policy issues and human, international, national, and political dimensions. After traveling to Bosnia, for example, he discovered that although the thousands of buried mines there pose a threat to the population, they also serve to keep borders intact and help to discourage an attack from neighboring rival factions. Despite the complexities of the demining problem, he believes that "Livermore, with its intellectual and technical smarts, is the right place to take on this issue, and the Center is the right place to look at the nexus of policy, technology, and security."

Looking to the Future

"We want the work done at the Center to be valued and respected by the best minds and institutions around the world," says Lehman. To accomplish that, he says, means reaching out more to University of California campuses and other academic institutions, as well as to industry, government, and international organizations.

The Center is also looking for ways to make its work more accessible. Lehman's goal is to have all of the research papers and workshop reports placed on the CGSR World Wide Web site (*www.llnl.gov/nai/cgsr-home*). He is also working with the University of California Institute on Global Conflict and Cooperation to use the Internet for electronic conferencing, part of a proposed "virtual diplomacy" initiative.

Lehman says the best measure of the Center's success is the degree to which senior officials and top-ranking experts desire to be CGSR participants and fellows and the interest, inside Lawrence Livermore and out, in using the fresh insights from its studies and workshops. Judging by recent history, including Janet Reno's keynote address in February, the CGSR is meeting Lehman's tough standards.

—Arnie Heller

Key Words: Center for Global Security Research (CGSR), Commission on Critical Infrastructure Protection, computer security, International Science and Technology Center (ISTC), Joint Verification Experiments (JVE), Lab-to-Lab program, land-mine removal, National Infrastructure Protection Center, nonproliferation, Threshold Test Ban Treaty (TTBT).

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