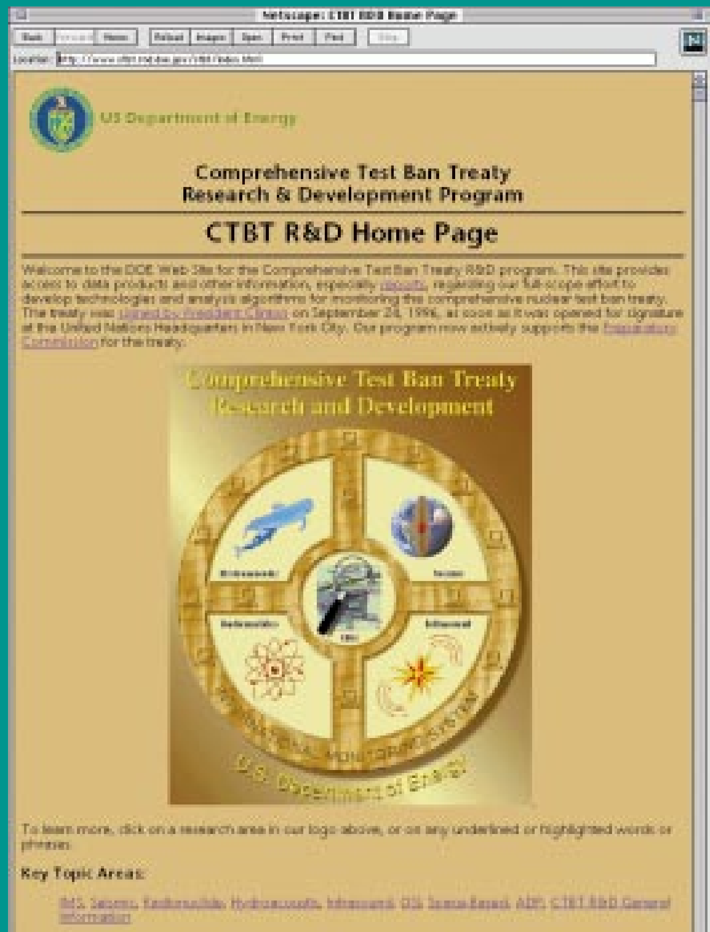
DOE/NN-98001802

Comprehensive Test Ban Treaty

Research and Development

Plans and Accomplishments



For more information

The DOE CTBT R&D Program World Wide Web Site (http://www.ctbt.rnd.doe.gov) provides a means to disseminate information about our program and to share research products, data, and results among fellow researchers. It contains links to the Treaty text itself, including a keyword search tool. In addition, it contains information about the technologies being developed, the anticipated CTBT monitoring regime, and the major research laboratories involved. It also contains a comprehensive bibliography with tools to request copies of reports and display reports if they are available on-line. Data and tools to manipulate data are available on-line, as are links to other data sources. In addition, links are provided to other Web sites that contain information relevant to the Treaty.

During the PrepCom phase, we will continue to enhance the Web site to improve its ability to aid users in gathering information, coordinating research efforts, and working together in a collaborative environment. We will continue to look for Web-based tools that will improve CTBT R&D, particularly research coordination and product integration. We are also transferring our experience—including key personnel who developed our site—and Web-based tools to the international PrepCom/CTBT Organization, who inaugurated their Web site (http://www.ctbto.org) on the first anniversary of the Treaty's being opened for signature.

. . . from Signature to Entry Into Force

http://www.ctbt.rnd.doe.gov

U.S. Department of Energy

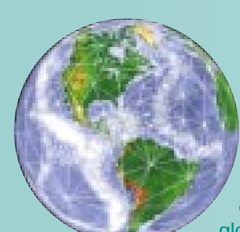
The United States Department of Energy (DOE) views the Comprehensive Test Ban Treaty (CTBT) as an important contribution to national security. It begins an era of global security gained by monitoring all of the earth's environments. DOE has the expertise, the facilities, and the experience to help achieve the President's goal of an effectively verifiable CTBT. We believe this Treaty is a significant step toward reducing the nuclear danger, and we are committed to providing long-term scientific and technical support to Treaty-monitoring operations.

Federico Peña, Secretary of Energy

As the international community moves toward Treaty implementation, research and development (R&D) support to operations becomes a stronger focus of our program. While the specific International Monitoring System technologies were selected in part because of their maturity, continuing R&D is needed, as recognized by the President in his statement of his commitment to a zero-yield Treaty on August 11, 1995. This brochure describes the high-priority R&D that we are pursuing in the DOE CTBT R&D Program, and how it will support effective CTBT monitoring.

I am interested in receiving your comments about our program; you are invited to call me (202-586-2151) or comment through the Feedback feature on our Web site (http://www.ctbt.rnd.doe.gov).

Leslie A. Casey, CTBT Research and Development Program Manager



On the cover:

One of the major challenges in Comprehensive Test Ban Treaty monitoring is rapid analysis of data for specific regions of the world. Accomplishing this task requires detailed information about the world's various regions. This information can be managed with techniques such as the tessellation used here to produce a grid based on global earthquake data. The intersections on the grid represent the locations of known data values; these values will be used to interpolate intermediate points within a triangular area. Similar tessellations are being developed region by region by the Department of Energy's Comprehensive Test Ban Treaty Research and Development Program.

Print date: June 1998

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The Comprehensive Test Ban Treaty:

Signature Begins the Next Treaty Phase

Treaty Signature . . .

Each State Party 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 State Party undertakes, furthermore, to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapon test explosion or any other nuclear explosion.

— Basic obligations of the Comprehensive Test Ban Treaty

Photograph courtesy of the White House

. . . to Entry Into Force

The Preparatory Commission for the Comprehensive Test Ban Treaty Organization (CTBTO) has its headquarters at the Vienna International Center in Austria, as will the CTBTO after the Treaty enters into force.

This document describes U.S. Department of Energy research and development in support of the Comprehensive Test Ban Treaty.

The signing of the Comprehensive Test Ban Treaty (CTBT) in September 1996 was a turning point in history, creating for the first time an international norm against all nuclear testing. It marked the end of the negotiations phase of the long-sought Treaty and the beginning of the preparatory phase that will lead to the Treaty's entry into force. The preparatory phase is organized around two main activities:

(1) Building the international verification regime (the key element of which is the CTBT worldwide network of sensor stations, the International Monitoring System) that will monitor global environments to ensure that the Treaty is not violated; and

(2) Gaining ratification of the Treaty by States Signatories.

An international organization, the Preparatory Commission (commonly known as PrepCom), has been established for this phase. The PrepCom is the precursor to the Comprehensive Test Ban Treaty Organization that will come into existence at Treaty entry into force.

At the U.S. Department of Energy (DOE), our CTBT research and development mission is to carry out research and development for the U.S. agencies responsible for monitoring compliance with the CTBT and for operating the U.S. National Data Center for CTBT monitoring; we provide technologies, algorithms, hardware, and software for systems to detect, locate, identify, and characterize nuclear explosions in a cost-effective manner at the thresholds and confidence levels that support U.S. goals. In addition, this CTBT R&D Program supports the PrepCom in numerous ways.

In this report, we describe our research and development in the context of the data flow in the future international CTBT verification regime. This regime merges four complementary technologies (radionuclide, infrasound, seismic, and hydroacoustic) into one system to collect and analyze data from the earth's atmospheric, underground, and oceanic environments. The data flow from these environments is collected by the International Monitoring System. Then data-interpretation techniques are applied to detect, locate, and identify prohibited explosions. Finally, ambiguities are resolved by consultation and clarification measures and (if warranted) by on-site inspection.

The data flow is illustrated in detail on pages 4 and 5. The sections that follow summarize

- The CTBT monitoring challenges (page 6).
- DOE's contributions and products during the negotiations phase (page 7).
- Research and development priorities (page 11).
- DOE's continuing work during the PrepCom phase for each of the CTBT technologies at each stage of the data flow (page 12).

We close with a brief history of the CTBT and a timeline for our major R&D products on pages 30 and 31. Additional information is available on our World Wide Web site, described on the back cover.

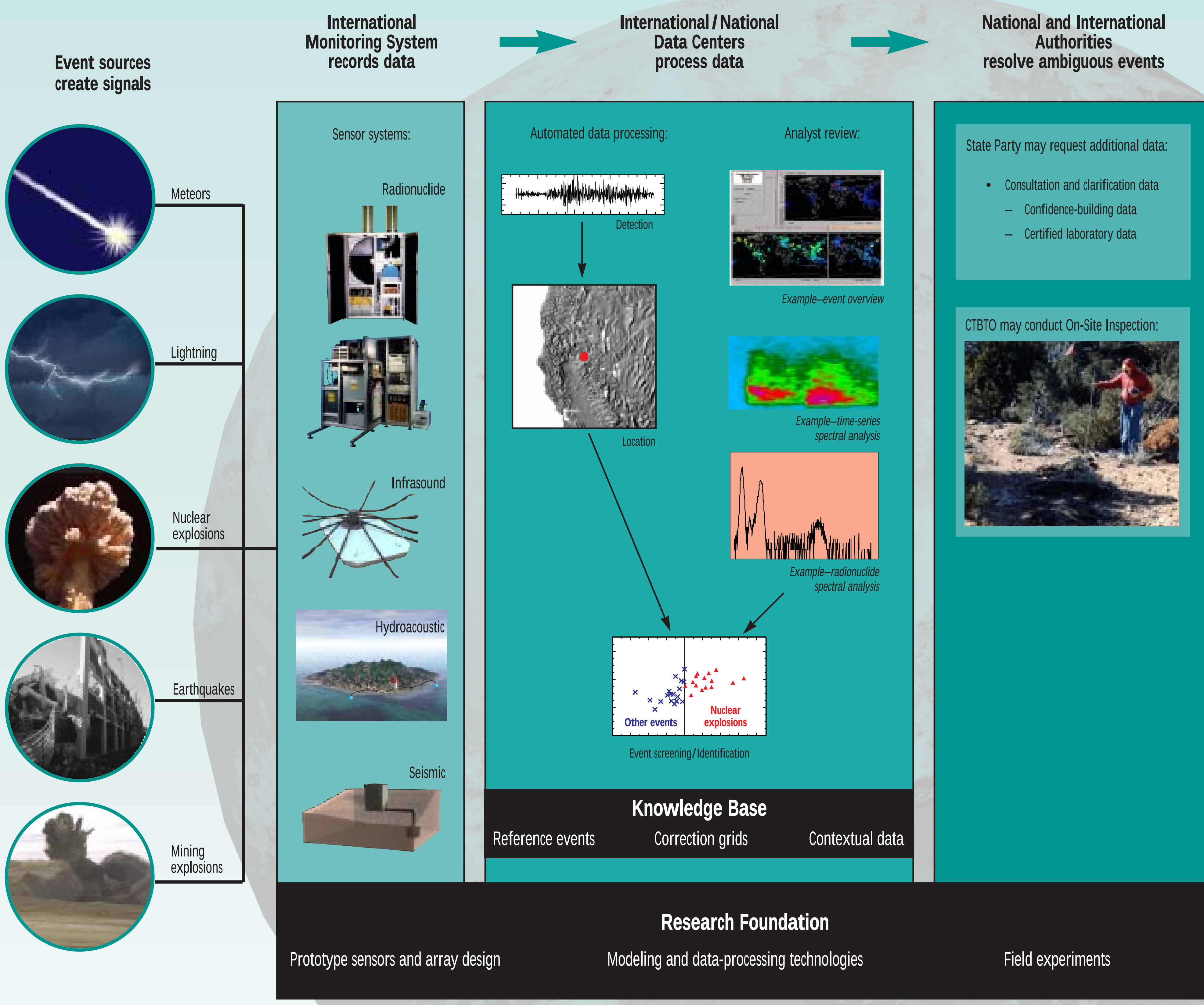
Data Flow in the CTBT Verification Regime:*
From the Sensors to the National Authorities

In the CTBT verification regime, the search for evidence of a nuclear explosion begins with the sensors in the International Monitoring System (IMS). The atmosphere is monitored by radionuclide and infrasound systems, the ocean by hydrophones and island ("T-phase") seismic stations, and the underground environment by seismic stations. These stations transmit data via a global communications network directly to data centers.

At the International Data Centre (IDC), the data are automatically processed to **detect** and **locate** events, producing a daily event bulletin that is available on-line in near real time to States Parties to the Treaty. In addition to the event bulletins, States Parties may receive any or all of the data at their own data centers. Each State Party makes its own assessment of the events, and may also use evidence gathered by its own national technical means such as satellite-based sensors. Since analysis capabilities and requirements vary from one State Party to the next, the IDC is designed to provide a range of products and services, from raw data to event bulletins that make use of agreed-upon screening criteria.

The challenge to all parties is to **identify** events—to distinguish data coming from a banned nuclear explosion from similar data from many other sources, such as earthquakes, lightning, meteors, and mining explosions or collapses. Human analysts at national data centers review and refine the results of the automatic processes leading to identification, and focus on ambiguous events. The vast amount of detailed global-scale information to be used by both the automated processing systems and the human analysts to detect, locate, and identify events will be stored and managed in some suite of integrated databases. Conceptually, this is represented in this illustration as a Knowledge Base, which would include reference events, corrections grids, and contextual data relative to all of the monitoring technologies. The DOE's research program provides a foundation for all components of the verification regime over the long term by developing prototype sensors and sensor arrays, by advancing computer modeling and data-processing technologies, and by conducting field experiments.

The Treaty makes it clear that the responsibility for compliance assessment, which requires a combination of technical and political judgment, resides with the States Parties and that the purpose of the IMS and the IDC is to support the States Parties in this effort by providing information to help them make these judgments. If a State Party's assessment is that a violation may have occurred, the Treaty prescribes that its National Authority may request more data from the IDC or another State Party and may request that the Executive Council of the Comprehensive Test Ban Treaty Organization (CTBTO) initiate an on-site inspection. The Executive Council is then obliged to consider the merits of the case and may request additional data from the appropriate States Parties for review. When making a request for an on-site inspection, a State Party is allowed to introduce evidence acquired by its own national technical means in support of its case.



* after entry into force

CTBT Monitoring Challenges: DOE's Contributions and Research Priorities

Challenges

The principal challenges in CTBT monitoring are to detect very-low-yield nuclear explosions as well as nuclear explosions conducted under conditions that mask the signals produced, and to distinguish them from other sources. The task is complicated by the similarities between effects from nuclear explosions and effects produced by non-nuclear sources. For the verification regime to be able to meet these challenges, work remains to be done in sensor development, in data management and analysis techniques that will ensure timely assessment of events, and in data collection to calibrate the sensor networks.

Sensors

To ensure that effects from a nuclear test in any of the earth's environments will be detected, the CTBT calls for an International Monitoring System containing networks of atmospheric, underground, and oceanic monitors: two types of airborne-radionuclide sensors, infrasound arrays (groups of sensors at one site), seismic sensors and arrays, and hydroacoustic sensors.

These sensor systems were selected for Treaty monitoring in part because their capabilities complement each other. Many natural or human-induced non-nuclear events can produce signals that, to a single sensor technology, may appear similar to those from a nuclear explosion—perhaps causing a false alarm. Furthermore, background noise or other interferences can mask or reduce the quality of evidence from events of interest for any of the technologies—perhaps causing an event to be missed. Improved sensors, sensor arrays, and networks will increase the monitoring ability to detect nuclear explosions and distinguish them from innocuous events.

Data Management and Analysis

Data collected by the IMS sensors will flow continuously to the international and, when requested, to the national data centers, where automated computer systems will preliminarily process them to detect and locate events. *Detection*, the first step in monitoring, is the process of finding a signal from an event in the stream of background noise. Once a detection has been made at a single sensor station, it is associated with signals at other stations to form an event. Then the *location* process uses the times and apparent directions of the detections to determine where and when the event occurred. When the location is known, event characteristics such as magnitude and frequency content can be determined and used to identify its likely source. Although event screening may be performed at the International Data Centre, the ultimate responsibility for assessing compliance with the Treaty—the *identification* process—lies with the States Parties.

Although the process is straightforward in concept, there are many challenges that must be successfully overcome. Consolidating gigabytes of data from different technologies in a single data-analysis system with little time delay presents a technological challenge for continuous communications, operation of automated signal-processing systems, and complex integration of data.

Network Calibration—Compensating for Propagation Effects

To achieve accurate location and identification capability, the sensor networks must be calibrated. To do this, detailed information is required about the paths over which signals could travel to a station. In general, as a signal propagates from its source, it is attenuated (weakened) and altered in many ways by the path that it takes. In some cases there is very little alteration; in others it is significant.

In the seismic case, we know that geologic structures in the earth's crust and mantle can have a significant effect on the travel time and amplitude of a seismic wave, and that certain geologic features block the transmission of some phases of the wave. Accurate location and identification are possible only after these effects have been taken into account. To map these features for a given region we use reference events—well-known historical seismic events, such as mining explosions and well-located earthquakes.

The other sensor technologies face an additional complication in that the path properties vary with time. For example, propagation of infrasound signals and radionuclide debris depends on wind conditions, and current meteorological data are required for analysis. For the hydroacoustic system, the temperature and salinity of the oceans at the time of the event are needed.

Calibrating the networks is a large, but achievable, task that requires a detailed understanding of the earth's interior structure, its oceans, and its atmosphere.

DOE's Contributions

Understanding the nuclear source is a key to effective monitoring of the CTBT. DOE's extensive experience in conducting nuclear tests makes us the primary source of knowledge about nuclear weapons. This was an important factor in why DOE was given the responsibility to carry out CTBT research and development for the U.S. government.

Our work began in earnest on this task during the negotiations phase of the Treaty.* We have made significant progress—DOE technology is being used in all aspects of U.S. CTBT monitoring and verification. We added unique features to our radionuclide and infrasound prototype sensors to make them meet international monitoring specifications. We made significant advances in seismic characterization and calibration of seismic event detection, location, and identification techniques for regions of critical monitoring interest: the Middle East, North Africa, and Asia. In addition, DOE scientists and engineers played key roles in supporting CTBT policy development, both in Washington D.C. and in Geneva, where Treaty negotiations were held. Descriptions of some major contributions of the DOE research and development effort during the negotiations and early PrepCom phases follow.

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* For a summary of DOE CTBT work during the negotiations phase, see *Ensuring a Verifiable Treaty*, CTBT R&D Program 1995 Progress Report, U.S. DOE, Washington, DC, Report No. DOE/NN-96005281 (available for viewing on the CTBT R&D Program web site, http://www.ctbt.rnd.doe.gov).

Radionuclide—Airborne Evidence of a Nuclear Test

Since World War II, DOE and its National Laboratories (and their predecessors) have been leaders in the development of instruments and techniques for the detection of nuclear radiation and radioactive materials. This technology and expertise was used not only for measurements intrinsic to nuclear science and engineering, but was (and still is) required for monitoring occupational exposures and environmental contamination. For decades, the most sensitive technology for detecting and identifying radionuclides required highly skilled scientists or technicians as operators, and environmental samples typically had to be returned to a laboratory if they were to be analyzed for radionuclide content.

The physics required for radionuclide collection and analysis for CTBT monitoring is no different from earlier DOE technology; however, the application to regional monitoring required several new developments. We created the first stand-alone, high-sensitivity, high-volume automated sampler / analyzers for radionuclide particulates and gases that report results in near real time. Our goal was to make sure that this re-engineered technology was available to any State Party, and we are well on our way to accomplishing this by transferring the technology to commercial partners.

Infrasound—Monitoring the Atmospheric Environment

DOE has unique, broad, and long-term expertise in infrasound monitoring, having maintained the only infrasound research group since the Limited Test Ban Treaty stopped atmospheric nuclear testing in the 1960s. We have a wide range of experience, including fielding equipment, recording and analyzing signals, and understanding both the source physics and the propagation physics that affect the signal.

During the CTBT negotiations, it became clear that infrasound would play a key role in monitoring; thus we undertook the development of a turn-key infrasound system that could form the basis of the infrasound component of the International Monitoring System. This system is currently being commercialized so that it can be made available to the international community.

We have extensive field experience in some of the environments where infrasound stations that are crucial to U.S. monitoring interests are being located, including island and arctic sites. We are in a unique position with prototype arrays to look at enhanced array design and noise-reduction systems, as well as improved data-processing techniques. We are also involved in international collaborations in the areas of sensor calibration, for which we have a specially designed facility, and field experiments.

In addition, we continue to play a leading role as the international infrasound community prepares to monitor the CTBT. In 1997, DOE hosted an international infrasound workshop. In collaboration with the Provisional Technical Secretariat of the CTBT Preparatory Commission, the workshop resulted in a set of recommendations for high-priority research topics related to infrasound monitoring, including array design and noise reduction.

Seismic—Monitoring the Underground Environment

DOE's interest in seismic monitoring dates back to the early 1960s when we began seismic recording for the Plowshare Program, which explored the use of nuclear explosions for peaceful purposes. When Plowshare ended, we shifted our effort to monitoring nuclear test ban treaties. For treaties previous to the CTBT, monitoring at great distances was adequate to record the allowed events of interest. However, regional monitoring—that is, within 2000 kilometers—is necessary to record the small events of interest under the CTBT. Monitoring at regional distances is more difficult because the seismic energy reaching the monitoring station has traveled primarily through the earth's crust, which has rapidly varying properties from region to region throughout the world. These regional differences must be taken into account when interpreting seismic monitoring data.

To achieve our monitoring goals in regions of interest we began a major effort during Treaty negotiations to seismically characterize the Middle East, North Africa, and Asia—cataloging and characterizing the differences between regions in order to calibrate techniques for event detection, location, and identification. At the beginning of the PrepCom phase we began a similar effort for the Former Soviet Union. The key first step in these efforts was the collection of a large set of seismic reference events—events for which the location, depth, and source type are well known. These events provide the raw data that we use to develop and test algorithms to detect, locate, and identify seismic signals. By the end of the negotiations we had more than 20,000 events in our database.

An important aspect of monitoring is the ability to effectively locate and identify events. During the negotiations it was established that events must be located within 1000 square kilometers or less for on-site inspection to be effective. We developed a correction methodology for location algorithms to reach this goal; using our reference-event database, we began cataloging the necessary regional corrections. Identification algorithms must be able to discriminate between natural events, such as earthquakes, and man-made events, such as explosions. A further step is to determine, whenever possible, whether an explosion is chemical or nuclear. The ultimate goal is to achieve an acceptable tradeoff between false alarms (detected events for which we cannot rule out a nuclear source) and missed violations (nuclear events that we fail to identify as such). During the negotiations we began to develop and test identification algorithms in regions of interest using our reference-event database.

In addition to the regional research, we began an effort to improve our understanding of the physical effects that influence the efficacy of our location and identification procedures. These efforts include theoretical and modeling studies, as well as field experiments. The calculational studies include modeling of the effects of source geometry, of near-source geologic structure, and the influence of sedimentary basins and other features on regional seismic propagation. We were able to accurately predict the arrival time and amplitude of key regional waves for selected areas in our regions of interest. Ultimately, the results of these modeling studies can be used to produce synthetic waveforms for areas where we do not have adequate coverage with reference events.

Our field experimental program focused on understanding the source effects of mining-related seismic events. An earlier DOE experiment, the Non-Proliferation Experiment (1 kiloton of chemical explosive fired in an underground cavity at the U.S. Nevada Test Site near the sites of previous nuclear explosions) had shown that the seismic signals from nuclear and single-point chemical explosions are virtually identical. Since mining explosions are generally not single-point explosions, but rather are distributed in space and time, we undertook a program of recording and analyzing local and regional signals from mining blasts to characterize the effects of the distributed source. We carried out a similar program in recording mining collapses. Since mine collapses and accidental deviations from planned delay-firing techniques can result in signals that closely resemble large simultaneous-explosion sources similar to a nuclear test (and therefore could cause false alarms under the CTBT), we worked with the U.S. mining industry to identify ways standard blasting practices can be modified to reduce these false alarms. Another important part of our seismic field program focused on investigating the effect of the depth of burial of an explosion on regional seismic waves, which will assist our ability to distinguish explosions from earthquakes. These experiments were done in cooperation with U.S. and foreign government agencies.

Hydroacoustic—Monitoring the Underwater Environment

The database of nuclear explosions at sea is limited to a few tests carried out years ago by the forerunner agencies to the DOE. Because the data are so limited, we developed a calculational capability to predict the effects of underwater nuclear explosions. We used this capability to carry out a series of network-coverage calculations to provide policymakers with options for achieving maximum hydroacoustic monitoring coverage within a limited budget. The calculations ranged from estimates of the acoustic field of view (and blockage) of each of a large number of candidate hydroacoustic sites to estimates of network location capability for several network alternatives. On the basis of these and other calculations, a number of sites making up a specific network geometry were recommended and generally accepted at the international level. Individual sites were chosen for their potential coverage of several ocean basins; the network was chosen to maximize overlapping coverage with a minimum number of stations.

The Knowledge Base—A Storehouse for Critical Regional Monitoring Information

For the monitoring system to work properly, massive amounts of data from individual monitoring sites need to be interpreted in terms of their regional settings—every day in real time. For example, the region-specific corrections to location and identification algorithms used in data analysis that we are developing need to be fed into the processing systems at the appropriate times. To carry out this critical task, DOE developed the concept of the Knowledge Base. The Knowledge Base is a database of regional, monitoring-station-specific parameters that can be accessed by the automated processing systems and human analysts at the U.S. National Data Center. Its purpose is integration of data and research results for all of the CTBT monitoring technologies. By collecting and managing the algorithms and regional contextual information and integrating them in data analysis, the Knowledge Base reduces uncertainty in location and identification of events. The concept and preliminary design of the Knowledge Base were completed during Treaty negotiations. Developing the Knowledge Base contents is our primary focus during the PrepCom phase.

DOE CTBT R&D is conducted in support of the U.S. National Data Center and other interagency organizations, which in turn support the U.S. efforts during PrepCom. DOE laboratories that conduct and coordinate major elements of the program are:

- Environmental Measurements Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratories

Other organizations funded by the DOE that have contributed to the CTBT through research and development are:

- Australian National University
- BBN, Inc.
- Bechtel Nevada
- Boise State University
- California Institute of Technology
- Chaparral Physics
- Columbia University
- Cornell University
- ENSCO
- Geophysical Institute of Israel
- Geophysical Services and Products
- Maxwell Technologies
- Multimax, Inc.
- New Mexico Institute of Mining and Technology
- New Mexico State University
- Radix Systems
- Ray Rashkin Association
- Science Applications International Corporation
- Scripps Institution of Oceanography
- Southern Methodist University
- St. Louis University
- Tracor, Inc.
- University of California–San Diego
- University of California–Santa Cruz
- University of Cambridge
- University of Texas–El Paso

Other DOE-funded contributing government agencies are:

- U.S. Geological Survey
- Naval Research Laboratory
- Army Corps of Engineers
- Defense Special Weapons Agency

The DOE will continue to seek out special expertise in whatever organization it resides to work on critical CTBT R&D issues. We anticipate that this will result in more international partners during the PrepCom phase.

Visit our CTBT R&D coordination Web site (http://www.ctbt.rnd.doe.gov/coordination) to monitor R&D contracts that have been funded by DOE, as well as contracts by other sponsors who are cooperating with DOE on product integration.

Research Priorities

During the PrepCom phase, we need to apply the results that we've obtained so far to support the building of the international verification regime. This regime must be built properly so that the United States and other States Signatories will have confidence that the Treaty can be effectively verified. Without such assurance there will be less incentive for States Signatories to ratify the Treaty. DOE is therefore providing specific research and development products that will enable the U.S. National Data Center to monitor effectively and rapidly. Remaining research priorities are described below.

Research Priorities for All Waveform-Data Technologies (Seismic, Hydroacoustic, Infrasound)

- Enhance network detection and location techniques to minimize false events and enable accurate location of events recorded on only a few monitoring stations. Since events of CTBT monitoring concern are expected to generate small signals, they will probably not be recorded on more than a few stations.
- Calibrate the IMS networks for accurate locations and event identification. Continue efforts to develop Knowledge Base reference-event databases to allow events to be interpreted in their proper regional context. Develop and test the parameters needed to implement detection, location, and identification algorithms. Develop advanced computation techniques that will enable the processing system to use the discrete data to analyze events at any location.
- Test identification algorithms on small-magnitude reference events from the regions of monitoring interest. Develop new algorithms for regions where current techniques are inadequate. These algorithms are crucial to rapid identification of events.
- Validate advanced waveform-modeling techniques for interpreting signals generated by new events. In regions lacking historic events, such techniques can be used to generate synthetic reference data. These techniques require the development of accurate geophysical models of the earth, oceans and atmosphere.
- Develop interpretation methods that take advantage of the synergy between the monitoring systems. Events that occur at interfaces between monitoring environments—for example, the ocean surface—will be recorded on two or more of the monitoring systems.
- Refine data-surety and authentication features of all technologies, including radionuclide.

Technology-Specific Research Priorities

- Radionuclide: Increase the commercial availability of the automated high-sensitivity near-real-time systems, enhance reliability, and provide tools to assist in understanding the data.
- Infrasound: Improve the signal-to-noise ratio through enhanced array design and optimized noise-reduction methods. Develop site-survey and station-installation procedures that will ensure optimal functioning of the infrasound network. Compile global wind data and develop advanced tools for improved understanding of propagation of infrasound waves. Enhance understanding of natural infrasound sources, such as meteors, to reduce false alarms. Make the sensor system commercially available.
- Seismic: Gather information on well-characterized reference events to complete reference-event databases; encourage States to offer access to such events (such as mining and other industrial explosions) through mechanisms such as confidence-building measures.
- Hydroacoustic: Calibrate the network for accurate location and event identification. Experimentally validate long-range acoustic propagation calculations and theoretical estimates of acoustic signals generated by nuclear sources underwater and in the low atmosphere. Calibrate hydrophone stations with near-field sources, determine acoustic coupling (signal strength) for T-phase stations, and check travel-times calculated for long paths traversing cold and shallow waters. Investigate synergy with the infrasound and seismic networks.

We will measure the success of our research and technology-development efforts by the following means.

- Radionuclide and Infrasound: by the commercialization of the designs, the availability of the systems at entry into force, and the number of stations ultimately using these designs to operate at CTBT specifications.
- Seismic and Hydroacoustic: by the degree to which the integrated research products help the United States reach its monitoring goals in regions of interest.

After the PrepCom phase, research focus will shift to verifying that the in-place International Monitoring System functions according to plan.

Keeping Watch on the World: Sensor Systems Collect Data

DOE-developed automatic systems for sampling and analyzing the atmosphere for radioactive nuclear test debris enable monitoring of detonation sites from several thousand kilometers downwind. The Radionuclide Aerosol Sampler/Analyzer Mark 4 fills the CTBT requirement for near-real-time ultra-sensitive field measurement of short-lived particulate fission products. The analyzer passes air through a filter for selectable time periods, then seals, barcodes, and performs a gamma-ray analysis of the filter. The gamma-ray spectrum and auxiliary data are transmitted to data centers. Filter samples are retained for subsequent analysis. DME Corporation is licensed to build and sell the system worldwide. This system won a prestigious R&D 100 Award in the independent competition sponsored by R&D Magazine in the summer of 1998.

Radionuclide and Infrasound Sensor Systems: From the Laboratory to the International Monitoring System

For the development of CTBT radionuclide and infrasound technologies, DOE has partnered with the U.S. National Data Center (NDC), as shown below. The NDC will operate the International Monitoring System stations in the United States.

• System specification	NDC
• Conceptual design	DOE
• Research and development	DOE
• Test and evaluation	DOE/NDC
• Contract for manufacturing	NDC
• Use	NDC

THE CTBT R&D Program is developing sensor technology in areas where DOE expertise can have the greatest impact. The four technologies were agreed to in the Treaty. One major focus of the PrepCom is to make these technologies available at the sensitivity, reliability, and economy necessary for CTBT monitoring. DOE's sensor R&D efforts are focused on developing the radionuclide and infrasound systems, miniaturizing the seismic sensors, and determining the best ways to deploy all of the sensors, including the hydroacoustic, at the sites specified in the Treaty. We are also developing hardware and software for data and system surety.

Radionuclide Monitors

Nuclear weapons tests release radioactive material into the environment. These gases and particulates may be detected by radionuclide sensors after dispersal by the wind. (Atmospheric explosions release the most radionuclides; however, underwater and underground explosions may also release significant quantities of radionuclides into the atmosphere under certain conditions.) The radionuclide-sensing part of the IMS is designed to detect such releases, and is the only IMS component that can confirm that an explosion is nuclear.

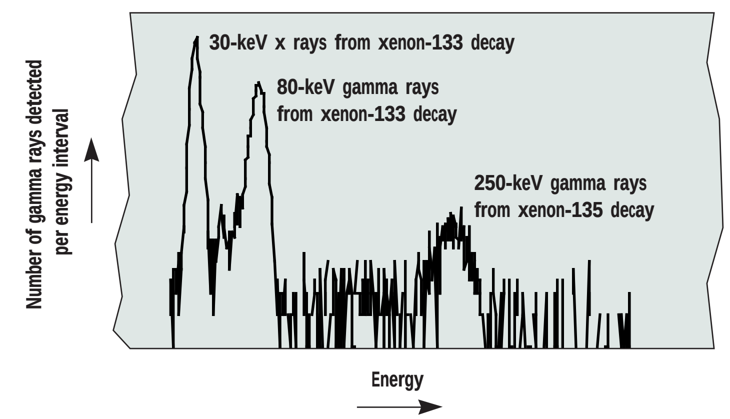
When the CTBT negotiations began, radionuclide sensors that could quickly and economically distinguish nuclear tests from other nuclear releases were not available. All of the sensors with sufficient gamma-ray-energy resolution required operators in the field, and laboratory analyses were required before results were available, limiting measurements to a few a week. It was necessary to develop radionuclide sensors specifically for the CTBT. Automation for increased reliability and reduced operating costs was the principal motive for re-engineering the technology, but more rapid data reporting was also important.

The IMS will have a network of 80 radionuclide stations. DOE developed prototypes of two automated self-contained instruments that meet the Treaty requirements; one detects airborne radioactive particles and the other radioactive isotopes of xenon gas. The instruments collect air samples, analyze the samples, and transmit data to the data centers. Each radionuclide station will ultimately contain both types of sensors, subject to Treaty installation protocol.

The particulate-monitoring prototype, the Radionuclide Aerosol Sampler/Analyzer Mark 4, was tested and evaluated by the U.S. National Data Center and selected as the basis for instruments to be installed at IMS sites on U.S. territory. The prototype particulate-monitoring system has been transferred to a manufacturer licensed to sell the systems commercially.

The xenon system, the Automated Radioxenon Sampler/Analyzer, is expected to follow the same development path. The prototype for the U.S. National Data Center commercialization effort also benefited from lessons learned in an independent test and evaluation.

The Automated Radioxenon Sampler/Analyzer performs ultra-sensitive analysis of four xenon isotopic gases in near real time. The xenon is collected on a charcoal sorption bed and is then thermally desorbed, purified, and measured by gamma-ray spectrometry. The gamma-ray spectra and radionuclide concentrations are transmitted to data centers. The gas samples can be retained for laboratory confirmatory analysis.



An example gamma-ray spectrum of radioactive isotopes of xenon gas detected by the Automated Radioxenon Sampler/Analyzer demonstrates its sensitivity. The system is able to detect and identify gamma rays even from xenon-135, which has a half-life of only 9 hours. The xenon-135/xenon-133 ratio is useful in distinguishing nuclear explosion debris from reactor releases.

In the DOE prototype infrasound system, each array of sensors is solar-powered and has a meteorological system (top). Each sensor with accompanying noise-suppression hoses is installed on top of a buried tamper-proof enclosure (center) containing the data-acquisition system and transmitter/receiver (bottom).

Infrasound Sensors and Arrays

A nuclear weapon test in the atmosphere releases large amounts of acoustic energy (sound). The sub-audible part of the signal (frequencies below 20 hertz) is called infrasound. Infrasound signals from even a small nuclear explosion can travel several thousand kilometers and still be detectable by specially designed microphones at infrasound stations. The Treaty specifies a worldwide network of 60 such stations. These systems contribute to successful monitoring since they provide a prompt method for detecting atmospheric explosions (it may take up to two weeks for radionuclides from an atmospheric test to reach a monitoring station).

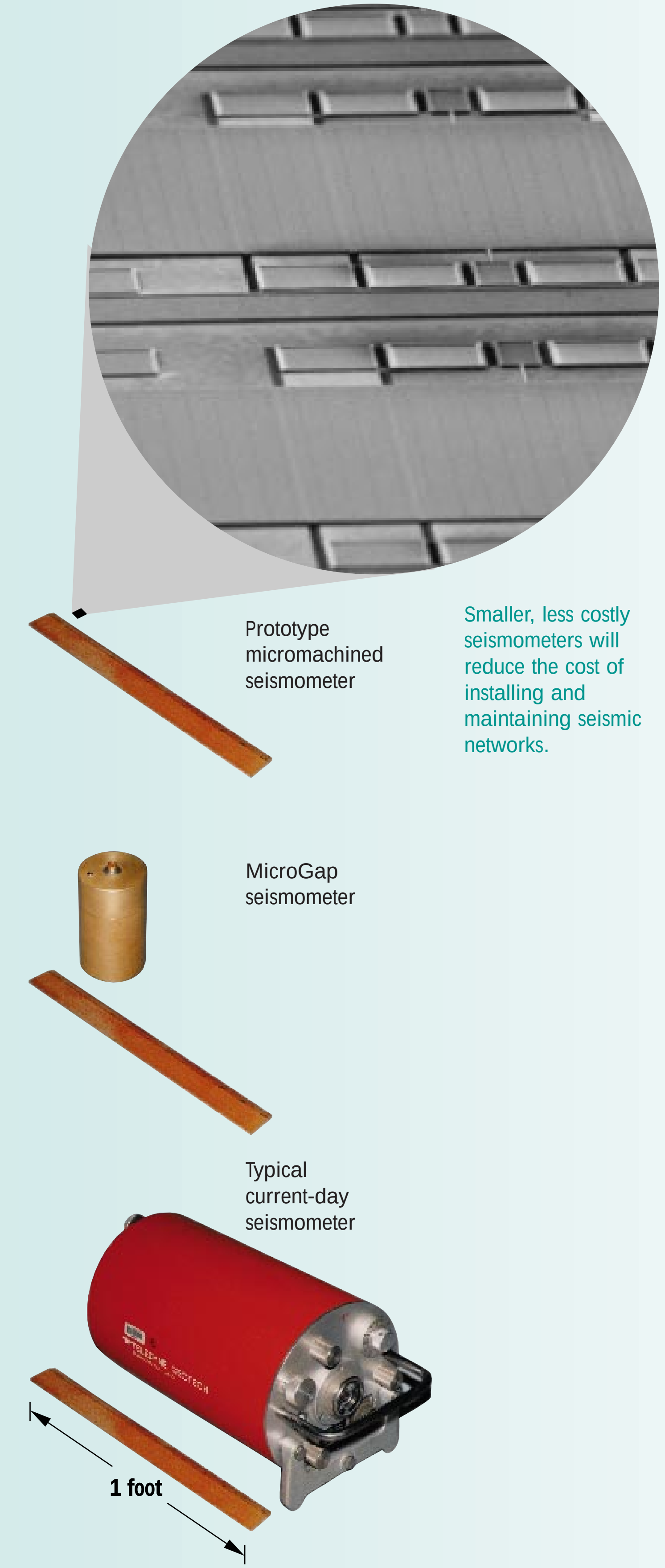
Infrasound technology was widely deployed until the Limited Test Ban Treaty banned atmospheric nuclear testing in 1963. The DOE has since maintained a small effort in infrasound research. Although infrasound sensor technology is relatively well understood, during Treaty negotiations there were no commercially available systems that met the specifications required to effectively monitor the CTBT. Since the start of the CTBT negotiations we have expanded our program and are developing an off-the-shelf prototype sensor that meets international requirements. We plan to document the system so that any country may procure and deploy a cost-effective system that meets the monitoring requirements. Users could procure the system from a single commercial integration vendor, or procure the components individually and integrate the system themselves.

We are also investigating optimal methods for operating groups of sensors in arrays. Although CTBT guidelines specify an allowed sensor-spacing range, we need to determine optimum site-dependent spacing within that range. In general, greater spacing improves bearing accuracy (accuracy in determining the direction of approach of the sound wave), but smaller spacing reduces noise and improves signal coherency. Our prototype infrasound array will operate initially with 1-kilometer spacing between sensors; an element with a spacing of about 2.5 kilometers will be added to study potential performance improvements. We are also analyzing historical data to obtain information on signal coherence at a spacing of a few kilometers.

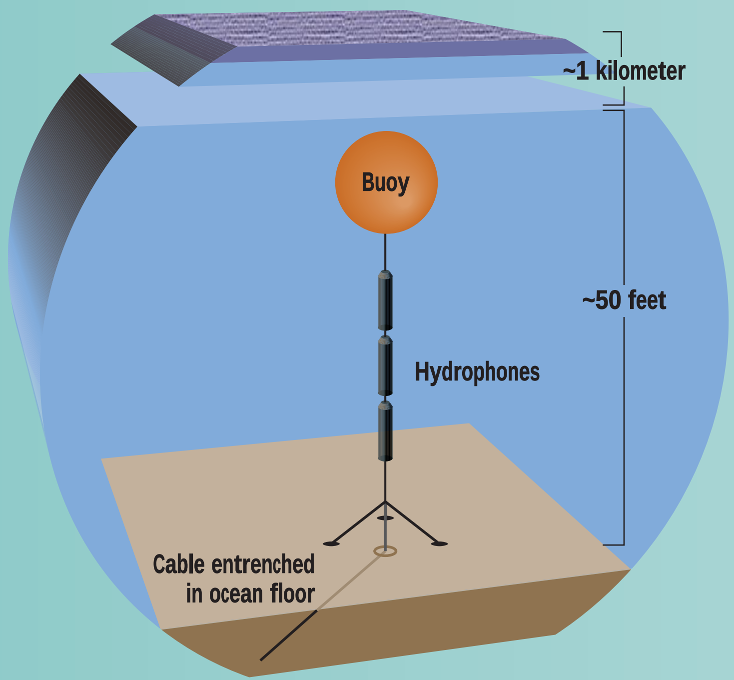
Seismic Sensors

Underground nuclear explosions create seismic waves. The seismic monitoring technology records regional seismic waves in the frequency range from a few hundredths of a hertz to a few tens of hertz. This technology is sufficiently mature that commercially available sensors are adequate for Treaty entry into force. However, smaller, less costly sensors could improve the reliability of future network upgrades and reduce installation and maintenance costs.

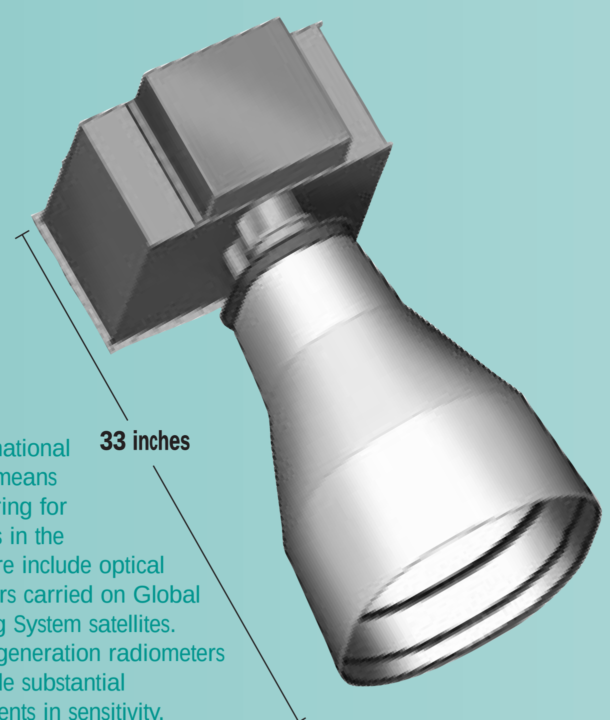
DOE is developing inexpensive, compact seismometers that require much smaller boreholes for deployment than do currently available sensors. One, the MicroGap seismometer, is in the process of being commercialized. The other is a micromachined seismometer that is still in the research and development phase. The tremendous advances being made in miniaturization and the capability to place the sensor and the electronics on the same chip make feasible a low-cost, small, lightweight, and low-power seismometer. The goal is a highly reliable micromachined sensor with high sensitivity and a wide bandwidth, capable of detecting signals above noise at the quietest sites. This research is made possible by leveraging with funding from other micromachined-development efforts. We have developed several approaches to the problem of how to develop the micromachining process to accommodate the large mass needed to sense the earth motion on the same computer chip as the electronics, and are now developing prototypes.



Smaller, less costly seismometers will reduce the cost of installing and maintaining seismic networks.



Existing sensor technology for the ocean-monitoring system meets CTBT requirements. At a typical hydrophone station, the sensors float above the ocean floor at a depth of about 1 kilometer.



The U.S. national technical means of monitoring for explosions in the atmosphere include optical radiometers carried on Global Positioning System satellites. Our next-generation radiometers will provide substantial improvements in sensitivity.

Hydroacoustic Sensors

Similar to atmospheric explosions, underwater nuclear tests release large amounts of acoustic energy (frequency 1–100 hertz) into the water. Because sound energy in the ocean is guided by temperature and density variations through the so-called SOFAR channel, the signals from underwater explosions can travel many thousands of kilometers and still have amplitudes large enough to be detected by underwater acoustic sensors (hydrophones). The Treaty specifies a network of six hydrophone stations and five T-phase stations (island-based seismograph stations that can detect an ocean acoustic wave when it converts to a seismic wave upon striking the ocean bottom near the island). The hydroacoustic monitoring network has significantly fewer sensors than any of the other networks because of the high efficiency of the propagation of signals in the ocean. Existing hydroacoustic sensor technology is relatively mature and sufficient for CTBT monitoring. Our research focuses on understanding detection and identification of nuclear-explosion sources in the oceans and on the integration of hydrophone and T-phase stations in the network.

Optical Satellite Sensors

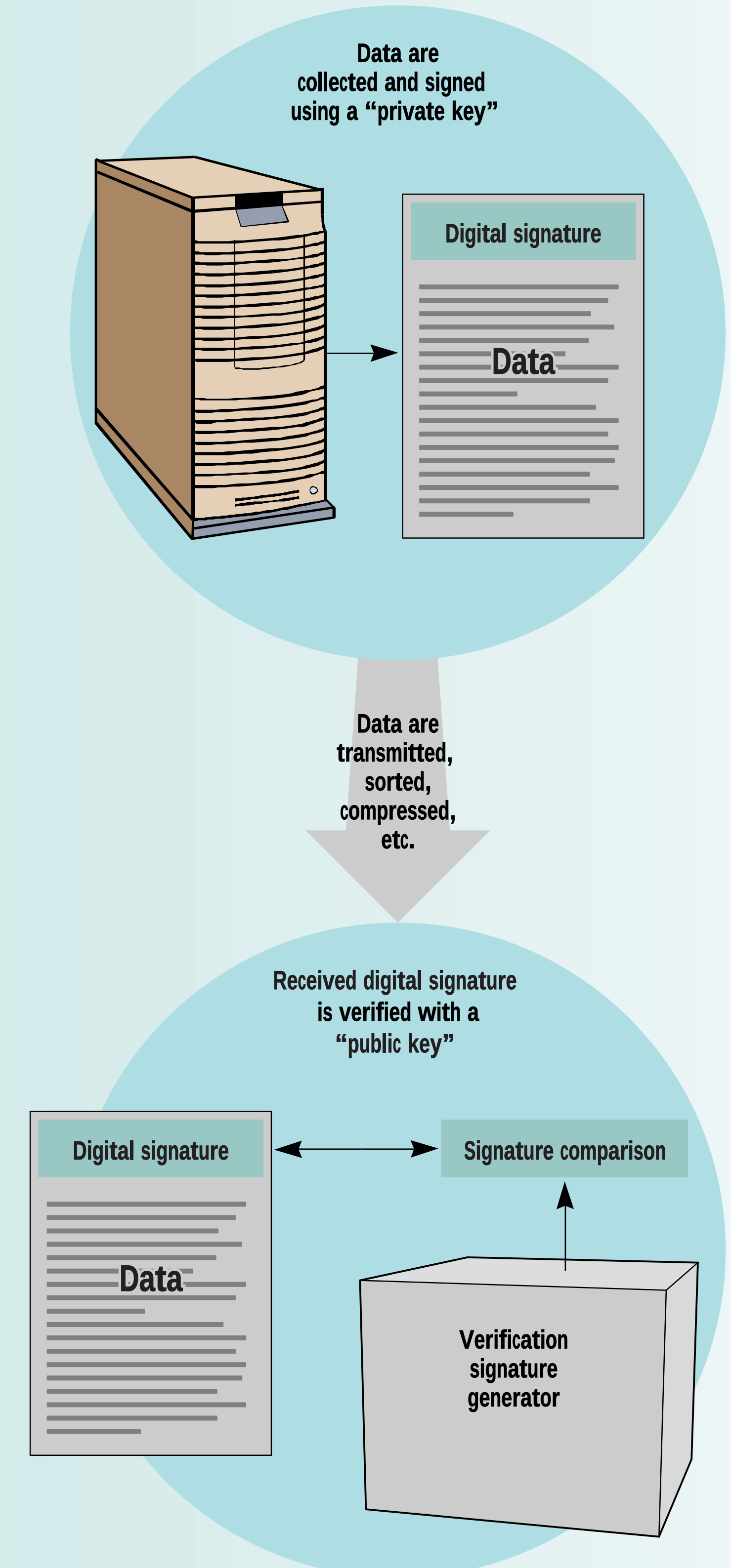
Beyond the IMS, the principal U.S. national technical means of monitoring for above-ground nuclear explosions reside on the Global Positioning System (GPS) satellite constellation. GPS satellites carry optical radiometers and electromagnetic pulse sensors for monitoring the atmosphere and x-ray sensors for monitoring space.

Optical radiometers (also called “bhangmeters”) detect visible and near-visible light. We are developing an improved-sensitivity bhangmeter that will fly on the next generation of GPS satellites. The sensitivity will be increased by using imaging optics and segmenting the sensing element. Each sensor element will view only a small portion of the earth, and the background noise in that element will be less than it would have been if viewing the entire earth. The result will be a substantial improvement in the signal-to-noise ratio and the sensitivity of each sensing element. Fabrication of this new-generation instrument requires state-of-the-art electronics design and packaging techniques to integrate a large amount of electronics into the sensor. Other issues being addressed include improvements in discrimination to reduce false trigger sources such as clouds and lightning.

Data Surety

The purpose of the four IMS technologies is to produce meaningful data, so data surety and integrity are essential—users must be confident that the data are authentic and have not been tampered with. Sensors need to be protected from damage or interference, either inadvertent or intentional, and the data they transmit need to be protected from corruption or falsification. To meet the challenge of developing a monitoring system that uses data from “open” / host-owned data sources and shares data with a variety of users, while at the same time ensuring data integrity and system security, our research assesses the data-surety needs of the IMS and investigates concepts for keeping monitoring data safe.

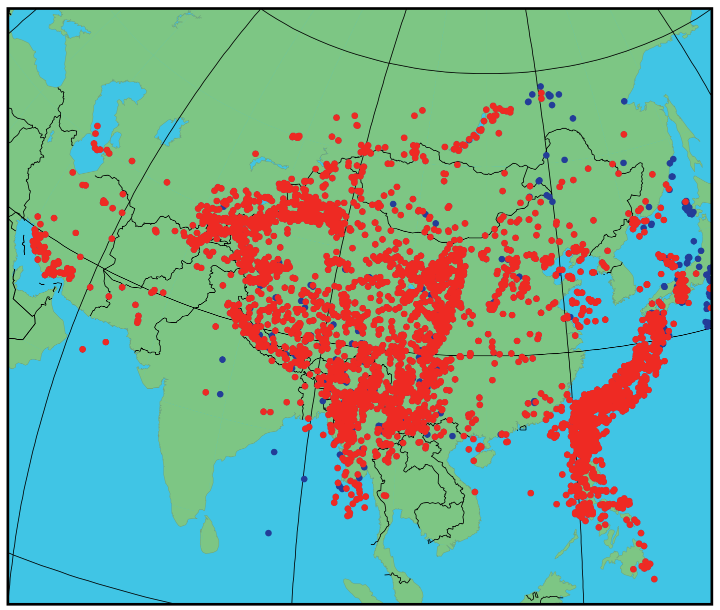
While data surety is not unique to CTBT, application to CTBT monitoring will entail tailoring to the specific IMS technologies. We focus on protecting specific elements of the IMS as well as the entire system. Data-surety measures we are developing include physical protection of monitoring equipment, electronic authentication of both data and commands, and procedural solutions.

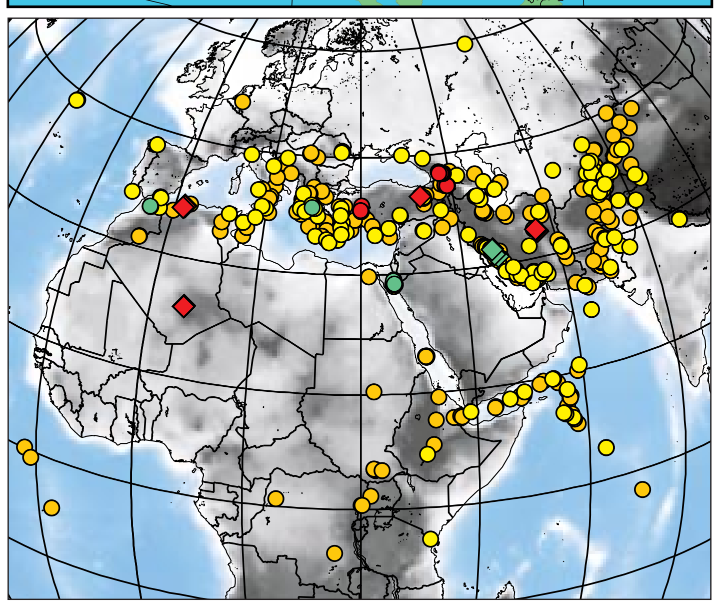


Data-surety measures include electronic authentication of data and commands as well as physical tamper protection.

Interpreting the Data:

Signal Analysis Using a Knowledge Base





Phase 1 of the DOE seismic reference-event data set is complete. The locations of reference events for Asia and the Middle East/North Africa that will be included in the initial version of the Knowledge Base are shown. Each dot represents a single event; the color represents further information on the event, for example, the type of information that was used to constrain the location. Developing these extensive reference-event data sets is required before the correction surfaces for the location and identification algorithms can be calculated.

The large quantity of data from the sensor network needed to monitor the CTBT requires that automated data processing be used in order to make accurate event detections, locations, and identifications in a timely manner. Both the International Data Centre and the U.S. National Data Center use a series of computer applications referred to as a “pipeline” to detect signals in the incoming data and associate those detections into events. The International Data Centre applies standard event-screening criteria to the detected events with the objective of characterizing and highlighting (and thereby screening out) events considered to be consistent with natural phenomena or non-nuclear man-made phenomena. The National Data Center must go even further and identify events, when appropriate. Once the automated processing is complete, trained analysts take over to further refine the event definition, location, and identification. The DOE CTBT R&D Program addresses all aspects of the U.S. National Data Center processing—faster and more accurate processing algorithms, more accurate parameters to drive existing algorithms, and tools to improve analyst capability.

The programs in the processing pipeline and the tools used by the analysts require knowledge about the earth, the oceans, and the atmosphere to provide accurate results. This knowledge, at the scale required by the CTBT, amounts to a vast quantity of information; a Knowledge Base is being developed to manage, store, and retrieve that information quickly and accurately.

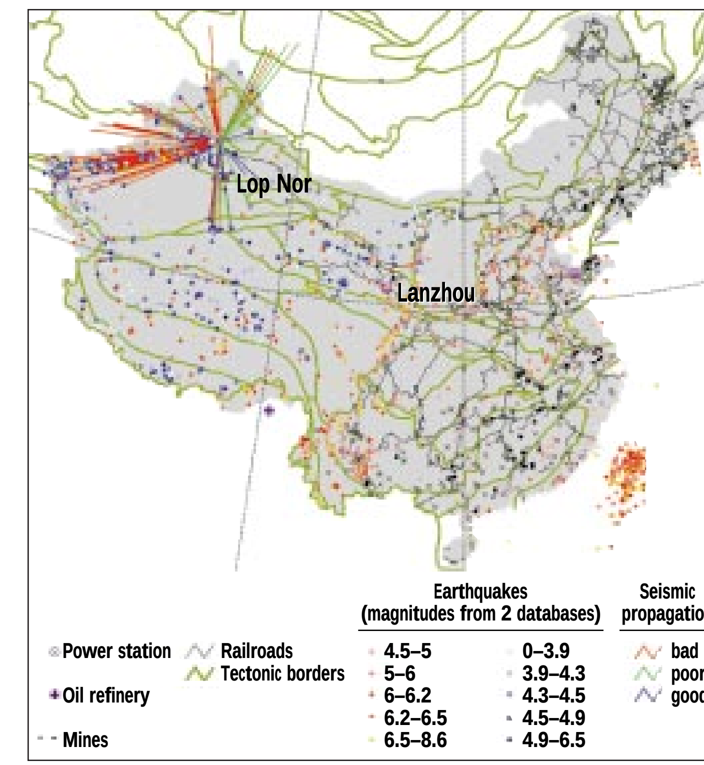
The Knowledge Base consists of both the content (the actual knowledge) and the underlying “engine.” The Knowledge Base content is being developed by DOE with input from a wide variety of agencies. DOE is integrating the information from these sources. The underlying engine provides structure to this knowledge and deals with the problems of efficient storage of large quantities of information, rapid and flexible access to that information, and maintaining the integrity of the information. The contents of the Knowledge Base will consist of three types of information: reference events, correction grids, and contextual information.

Reference Events. These are well-documented and characterized events in a given region. They can be compared against events of unknown origin and can be used to develop corrections for path effects. We are collecting and documenting tens of thousands of these events for inclusion in the Knowledge Base. Examples of reference events include space shuttle launches (for the infrasound case) and well-located earthquakes (for the seismic case)—events that are well characterized as to source, magnitude, location, and signal characteristics. Seismic reference events may also be carefully monitored mine explosions or dedicated explosions carried out specifically for calibration purposes.

Corrections Stored at Grid Points. The correction grids include the detailed parameters needed by the algorithms in the automated processing pipeline. Examples of such parameters are the point-based corrections to general global models of signal travel times, amplitudes, and azimuths. Each station in the IMS will require a detailed correction for each path that a signal might take from a source location to the station. Because the primary user of this type of information is the automated processing programs, a fast and efficient method of storing and retrieving this information is required.

Storing information for every possible source point on the globe is impossible because of the huge number of possible event locations, so a method must be found to accurately represent the correction parameters. We are modifying a sophisticated technique called kriging to interpolate between points where parameters are precisely known as a result of reference events. The primary advantage of kriging is that it allows both the interpolated data and its uncertainty to be represented at any given point on the globe. Once the kriging technique has been used to generate an accurate correction surface, a fast-interpolation technique is used to sample, store, and retrieve the kriged surface in the Knowledge Base. The fast-interpolation technique uses an irregular triangular tessellation to represent the surface in an efficient manner, similar to laying triangular tiles over an irregular surface; the triangles are small and numerous where the gradient of the surface is steep, but large where it is flat. The triangle node points consist of the original calibration points plus new points generated using kriging.

Contextual Information. The Knowledge Base will also contain information that can be used to put an event into context. This information consists of a wide variety of geological and geophysical data as well as geopolitical data (for example, mine locations and mining practices in a specific region) that are useful to an analyst in the final determination of the cause of an event.



Contextual information in the Knowledge Base is used to put data from reference events and new events into context. This region-specific information is important for determining the cause of an event. For example, one of DOE's products organizes information relevant to the Far Eastern geophysical regions for input into the Knowledge Base to support analyses.

Signal Detection: Spotting an Event

In detection, the first step in the data-processing sequence, the objective is to recognize a transient signal in the midst of background noise. Detection (and subsequent identification) must take into account the fact that many non-nuclear events can produce signals that appear similar to those from a nuclear explosion.
A detection is declared in a seismic, infrasound, or hydro-acoustic system when waveform parameters exceed a given threshold. Events are then constructed by associating individual detections using rules based on known travel times.

The Knowledge Base can improve this detection process by providing region-specific parameters (for example, station noise levels) to the detection algorithms.

Our Waveform Correlation Event Detection System (WCEDS) is a new, fundamentally different approach to event detection. It detects events directly in the raw signal data using the entire data stream from the global network of sensors. WCEDS offers opportunities to improve the overall monitoring system results by complementing the existing event-detection mechanisms and filling in for the weaknesses of traditional approaches.

A nuclear explosion may produce these effects . . .	when detonated in these environments
Seismic waves	Underground, oceanic, or near-surface atmospheric
Infrasound waves*	Atmospheric, near-surface underground, or near-surface oceanic
Hydroacoustic waves†	Oceanic or near-surface atmospheric
Radioactive particulates	Atmospheric, near-surface underground, or near-surface oceanic
Radioactive xenon gas	Atmospheric, near-surface underground, or oceanic
Optical flash‡	Atmospheric
Electromagnetic pulse‡	Atmospheric, near-surface underground, or near-surface oceanic

Other source phenomena . . .	produce effects that could lead to false alarms
Earthquakes	Seismic, hydroacoustic, and infrasound waves
Mining explosions	Seismic and infrasound waves
Mine collapses	Seismic and infrasound waves
Meteors, bolides§	Infrasound and seismic waves, optical flash
Sonic booms	Infrasound waves
Nuclear reactor operations	Radioactive gases
Nuclear reactor accidents	Radioactive gases and particulates
Natural radioactivity	Radioactive gases and particulates; gamma-ray and cosmic-ray flux
Lightning	Optical flash, infrasound waves, electromagnetic pulse

* Very-low-frequency sound waves.
† Underwater sound waves.
‡ These nuclear-explosion effects, best observed by sensors on satellites, will not be monitored by the International Monitoring System. The Treaty allows a State Party to use satellite-based systems at its own expense (as part of national technical means), and provides for the use of such data in a request for an on-site inspection.
§ Exploding fireball meteors.

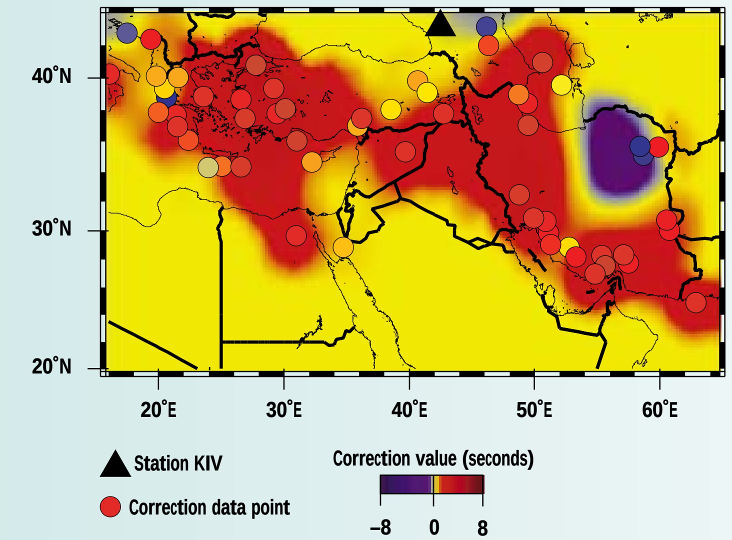
Event Location: Finding the Site of an Event

Once an event has been detected, its location must be accurately ascertained as a precursor to event identification and potential on-site inspections. The Treaty states that the area of an on-site inspection shall not exceed 1000 square kilometers; this sets the accuracy goal for event location.

The automated process for determining the location of an event from the recordings at the seismic, hydroacoustic, and infrasound monitoring stations is to assume an initial source location and apply a wave-propagation model. The computed arrival times of signals from that location to that station then are compared with the observed time. By iteration, the source location is changed in the model until the computed arrival times are within tolerance of the observed times. The location error depends on the error in the assumptions used to compute the arrival times. DOE's CTBT R&D Program is computing corrections and developing models that will improve the accuracy of these computed arrival times.

Correction Surfaces

In the seismic system, computation of travel times from global models of the earth is always approximate, since the earth's structure can vary dramatically in three dimensions. Errors in these models can lead to inaccurate event locations. We are developing region- and station-specific travel-time corrections that will allow the location algorithms to produce accurate results. These parameters are being represented as correction surfaces in the Knowledge Base. These surfaces are interpolated for every point in a region of interest using the modified kriging technique we have developed. Since not only the parameter itself but also the parameter's uncertainty are stored at any point, the uncertainty of the final location for an event can be accurately represented.



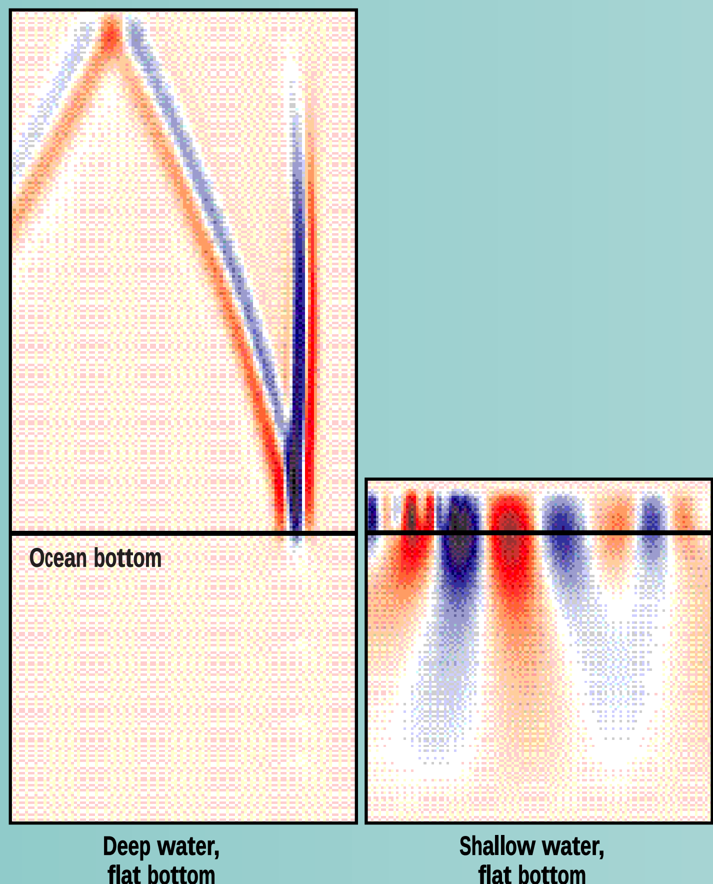
Region- and station-specific corrections to seismic-signal travel times are represented as correction surfaces in the Knowledge Base. In our preliminary correction surface for a subregion of the Middle East for seismic station KIV, the colored dots show the data and the color variations from red to blue show the values, in seconds, for the correction surface. Values read off this surface are used to correct the arrival times of seismic events at KIV that are used as input into event-location algorithms. We will develop similar correction surfaces for all of the key monitoring stations in our regions of interest.

Solid-Earth Models

For regions that don't have adequate reference events, we are developing geophysical models and calculating the corrections from these models. For example, we are developing seismic velocity models for North Africa and large areas of the Former Soviet Union, where there is very little natural seismicity.

Ocean and Atmospheric Models

The hydroacoustic (including T-phase stations) and infrasound systems also need models of the ocean and the atmosphere, but since these environments change from day to day and season to season, the corrections must be computed from a model and then applied to the location algorithm. In conjunction with a private contractor we are developing geophysical models of the oceans that vary with time. For infrasound, up-to-date atmospheric models can be used in propagation models to predict expected waveforms along specific source-to-station paths. We are working with the DOE Meteorological Coordinating Council to establish a Global Wind Data Center to serve as a central point for distribution of upper-atmosphere wind data relevant to infrasound signal propagation.



Ocean depth can have a large effect on the source signal of an underwater explosion. Here, in two wavefield "snapshots" for explosions in deep and in shallow water, the colors show the amplitude of the propagating wave. Note that the shallow-water case has a significantly different appearance and that more energy couples into the ocean bottom.

Event Identification: Classifying an Event

Understanding the typical signals generated by nuclear and non-nuclear sources under various conditions is key to event identification. As in event location, regional conditions can affect the way a particular monitoring station receives a signal and, if not factored into the analysis, could lead to false alarms or missed events. We are collecting data and conducting experiments to characterize sources and their signals for all of the monitoring technologies. We are also cataloging cultural features (such as nuclear power plant locations and emissions for the radionuclide system, and mine locations and practices for the seismic system) that can contribute to spurious signals.

Radionuclide Sources

Nuclear reactors are common sources of some of the fission products that the radionuclide system will detect and use to identify nuclear explosions. To be certain that reactor effluent will not compromise the identification ability of the xenon-gas sensors, we studied radioxenon concentrations in the northeastern United States, where there is a large number of reactors. The results prompted the inclusion of detection capabilities for two additional xenon species in our sensors. These short-lived radioxenon species are released from reactors in much smaller concentrations than are the longer-lived species, and the ratios of their activities can unambiguously distinguish the type of source.

Infrasound Sources

For the infrasound system, large meteors that explode in the atmosphere, called bolides, are one source of false alarms. To reduce this possibility, we are studying well-observed bolide events to determine how their signatures differ from those of nuclear events.

Hydroacoustic Sources

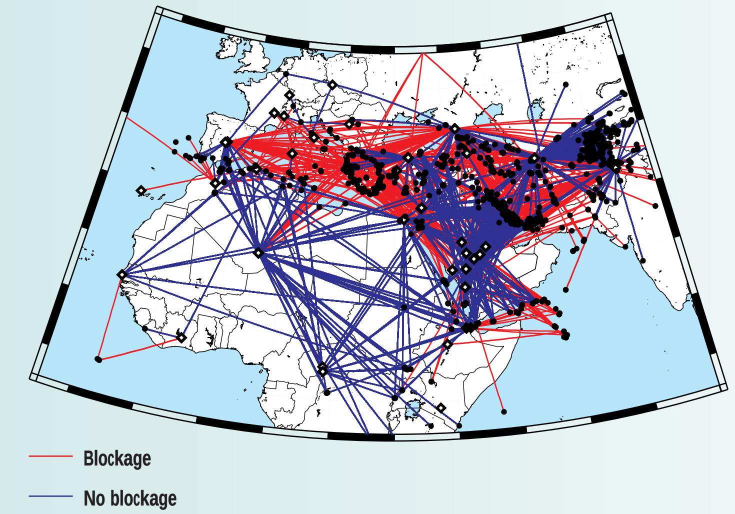
Few reference events are available for nuclear explosions in the ocean-monitoring environment. Our earlier work focused on using advanced calculational techniques to understand how nuclear explosions carried out near the surface of the ocean would be observed at hydroacoustic monitoring stations. Our work during the PrepCom phase uses similar techniques to develop source terms for various ocean-bottom configurations that are of importance to monitoring. To the extent possible, we plan to carry out scaled field experiments to verify the results of our calculations. We conducted an experiment in July 1997 to understand how acoustic energy is coupled into the water from explosions near the surface.

Seismic Sources

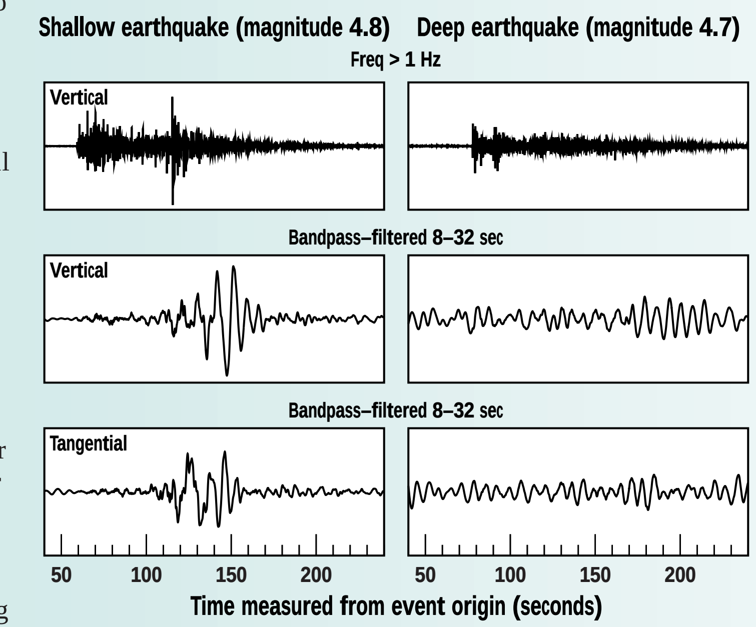
Natural and man-made sources will make the job of monitoring the underground environment especially challenging. Hundreds of thousands of earthquakes and mining explosions occur each year, and each one of these sources must be checked to see if it could be a nuclear explosion. In addition, there are rarer sources, such as mine collapses and volcanic eruptions, that also must be investigated carefully. For source identification to work properly, the source itself must be well understood, in addition to any alteration that the signal might have undergone traveling from the source to the monitoring station.

Seismic Calibration. *Regional Magnitude Scales*—Seismic magnitudes are important parameters in discriminating between explosions and other sources. They are the basis for some identification algorithms and they establish operating regions for others. However, they are difficult to estimate for small events when the seismic waves are recorded by only a few stations at regional distances. To minimize the variance in estimates between stations, we are calibrating regional magnitude scales using empirical measurements of attenuation of key regional seismic-signal phases such as Pg and Lg (compressional and shear waves) and also coda waves (late-arriving waves). Of these, the latter appear to yield the most consistent results across a region.

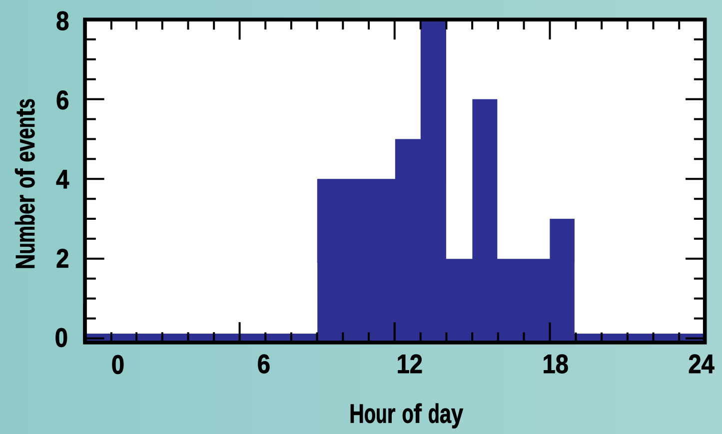
Shear-Wave Blockage—Seismic shear waves are a critical parameter in event identification. These shear waves are blocked by geologic structures in some regions; it is important to understand the blockage in order to correctly interpret the data. We are delineating areas of this blockage. For example, the eastern part of the Mediterranean blocks shear waves but the western part does not. This means, in this case, that the Sonseca station in Spain can be used to monitor events in some parts of North Africa but not others. Similar situations exist for other stations, so we are mapping blockages in regions of interest. In addition, other types of phenomena can be mistaken for blockage. For example, our analysis of shear-wave blockages shows that areas of known deep seismicity produce waveforms that can be mistaken for these blockages under the right conditions.

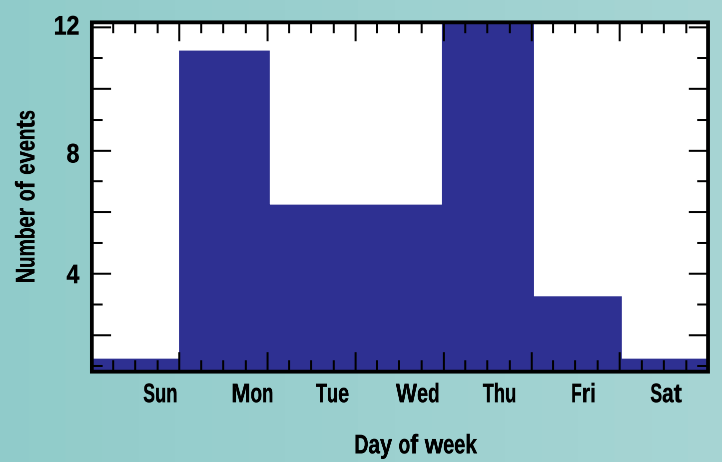


Seismic shear waves, a critical parameter in event identification, can be blocked by regional geologic structures. Analysis of these blockages allows us to determine which stations are the best to monitor a given region.



Identification using algorithms that incorporate shear-wave-blockage data must also consider other types of phenomena that can be mistaken for blockage. For example, we have found that some seismic waveforms that seemingly reveal blockage are actually produced by very deep seismic events under certain conditions. Here, two earthquakes with similar magnitudes recorded at station WMQ in China show very different waveforms—the deep-earthquake signal has no shear-wave component (the large amplitude in the center of the shallow-earthquake signal).





Mining explosions are useful reference events, but in regions with limited access, the challenge is to know which events are from mines. We know that mining explosions tend to occur at the same times of day. Cluster analysis reveals time patterns that are typical of mining practices in the region.

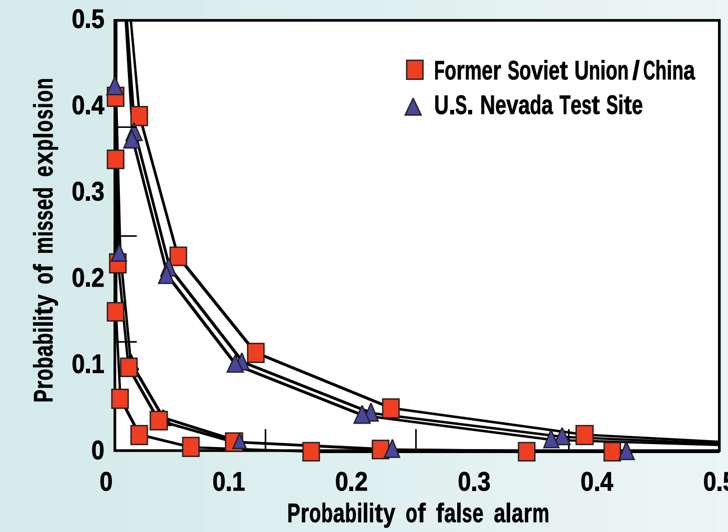
Mining Explosion Experiments—For seismic monitoring, characterization of mining explosions is particularly important, since they are a potential source of numerous false alarms. To better understand them, we have conducted experiments in cooperation with U.S. mining companies at several mines, for example, the Black Thunder Coal Mine in Wyoming and the Twenty Mile Mine in Colorado. These mines employ different practices—large surface blasts at the former and room-and-pillar excavation at the latter. Consequently, they create different types of signals, including collapses in the case of the latter. We have quantified the size and regional seismic characteristics of these different signals.

In regions where no nuclear explosion data are available to use to test the performance of identification algorithms, we are using mining explosions instead. In regions where we have limited access, the challenge is to determine which events are from mines. One way is to use the fact that mines tend to detonate their explosions at regular times every day—for example, during changes in working shifts. This criterion together with cluster analysis allows us to develop databases for algorithm evaluation.

Depth-of-Source Experiments—We are also conducting experiments to understand the effects of source conditions. Many regional seismic identification algorithms use measures of the shear-wave component of the seismic wave, yet the generation of these waves by explosions is poorly understood. Calculations suggest that shear waves are produced near the source of an explosion, perhaps by interaction with the earth's surface. Our experiment in cooperation with the U.S. Defense Special Weapons Agency's Cooperative Threat-Reduction Program at the former Semipalatinsk Test Site in Kazakhstan tested the effect of depth of burial of the source on the generation of shear waves, in order to refine shear-wave identification algorithms.

Seismic Numerical Models. In regions where we have no observed data, we can predict the effect of geologic structures on seismic phases. We have developed a wave-propagation computer code for this purpose. It can create synthetic seismograms for waves propagated over regional distances (up to 2000 kilometers) and has successfully reproduced earthquake and nuclear-explosion data from a number of paths in western China and the Middle East / North Africa region. Such modeling also allows us to determine what factors have the greatest potential effect on the signal so that we can focus our data-collection work on them.

Seismic Metrics. To show that our identification techniques are reaching our monitoring goals we have developed a metric—that is, an evaluation technique—to show progress. For a given identification technique, for example the seismic Pg / Lg algorithm, we can calculate the probability of failing to identify an explosion and the probability of a false alarm. Since there is always uncertainty in event identification, these two quantities trade off against each other. One way to show this tradeoff is to use a "receiver operating characteristic" curve: the best identification is achieved for the curve that is closest to the origin of the axes. For example, we can plot our identification results for events in the Former Soviet Union and China (recorded at seismic station WMQ in China) and compare them with similar results from the U.S. Nevada Test Site. The U.S. Test Site has been very well calibrated, and performance in this region provides a reference.



The goal for identification algorithms is to be able to differentiate between explosions and earthquakes in uncharacterized regions as well as we can at the well-characterized U.S. Nevada Test Site. Our algorithms based on ratios of seismic wave phases reach this goal. Here, application of three different algorithms to events in the Former Soviet Union and China (recorded at station WMQ in China), presented as curves showing the tradeoff between missed explosions and false alarms, gives results close to those at the Nevada Test Site.

Visualization tools assist analysts in interacting with the resources of the Knowledge Base. For example, a display of the tessellated globe shows the points (intersections of lines) where corrections for path effects are stored.

The Role of the Human Analyst: Evaluating Ambiguous Evidence and Integrating Results

Even with optimal automated processing, there will always be a need for a human analyst to evaluate the results of the system and manage the knowledge that drives the system's decision-making processes. Analysts will review the automatically processed events for false events—incorrect detections and associations from different stations—and missed events. In the latter case they can form new events by making the proper associations. Analysts also will review the results of the screening procedures to determine which events need closer examination. To minimize the manpower required for these tasks, the DOE CTBT R&D Program is working on several projects in data visualization, applying advanced techniques using shape, color, texture, and three-dimensional imaging. We are also developing tools for research on identification issues and for assessing system performance.

Data Visualization

DOE has produced data-visualization displays to present information needed by the data centers, such as a "quick look" display, an enhanced map display, and tools for station maintenance. We are developing visualization to support the building of the Knowledge Base and interaction with its resources—for example, to develop and refine the correction grids and to manage the voluminous and complex regional-effects data being collected and analyzed.

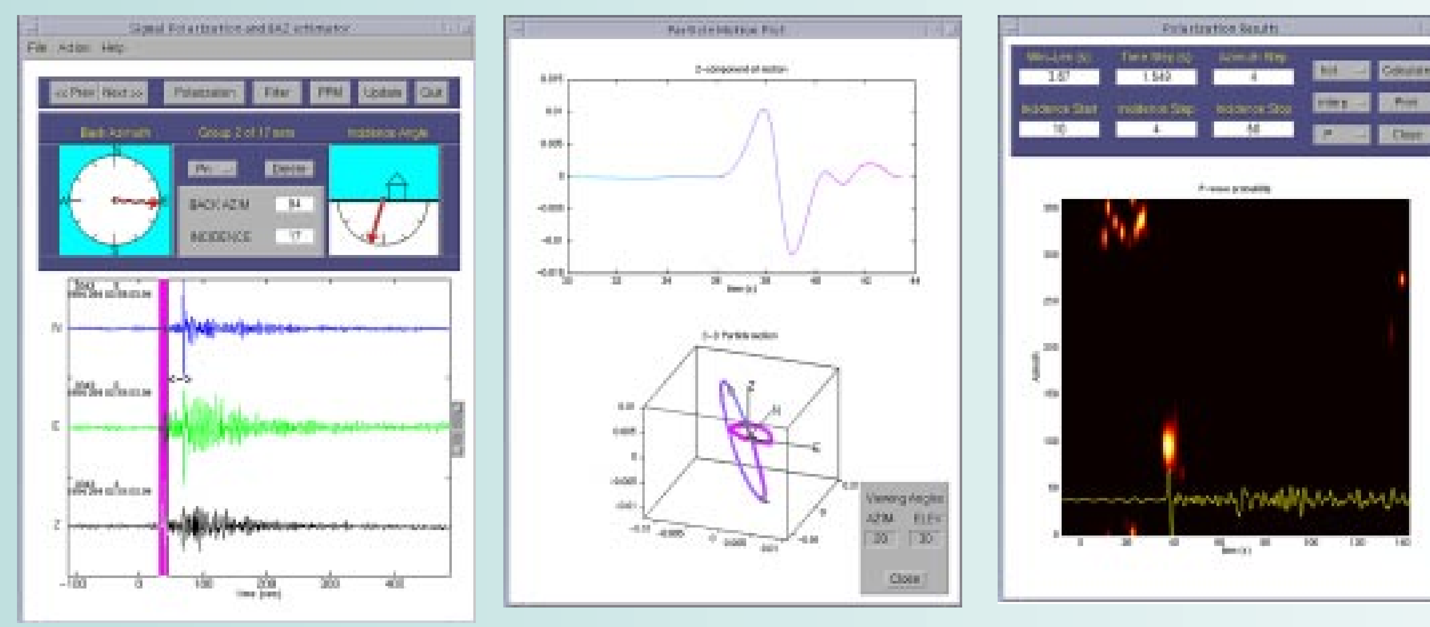
We are also developing a user interface to the Knowledge Base. This tool will be used by the analysts to access and manipulate data and to report their findings. We are working with the U.S. National Data Center to define functional requirements of the interface. We expect to develop a prototype that enables the analyst to bring together many diverse datasets, provides user-friendly access to spatial analysis tools, and facilitates reporting of analysis results using pictorial, tabular, and text formats. These tools will allow analysts to compare an event at a given location against different datasets within the Knowledge Base.

Interactive Analysis and System Assessment

We are enhancing the DOE-developed Seismic Analysis Code (SAC) to meet CTBT monitoring needs. SAC has been in wide use for more than 15 years in seismic observatories and research institutions; although written for seismic data, it is compatible with any data that can be expressed as a time series—all the data from the International Monitoring System except from the radionuclide system—and allows rapid automatic analysis of large amounts of data. Our new version SAC2000 adds analysis capabilities and interfaces to allow easy access to a wide variety of data formats. More than 150 institutions have requested and received copies of SAC2000.

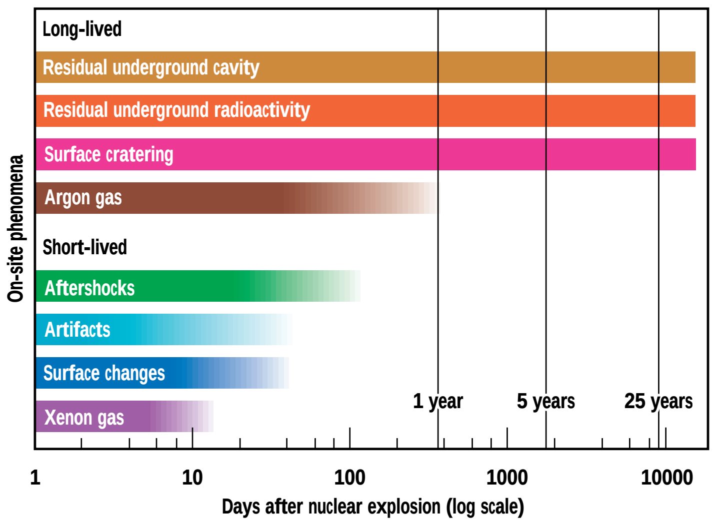
Another of our tools, called MatSeis, is based on the commercially available scientific computing program MATLAB that is widely used in industrial and university settings for solving research and engineering problems. MatSeis adds direct access to the database format used at the U.S. and International data centers, CTBT-specific signal-processing functionality, and an easy-to-use graphical interface. Users can express problems mathematically—allowing new algorithms to be prototyped and applied to real data in a fraction of the time that it would take to write a program in a computer language. MatSeis is available for downloading from the DOE's CTBT R&D web site *(see back cover)*.

Our Integrated Verification System Evaluation Model (IVSEM) is a computer program that allows the user to evaluate the performance of the entire monitoring system by exploring the impacts of sensor system concepts, configurations, and technology enhancements. It estimates the detection effectiveness and location accuracy for each monitoring system individually and for the full integrated system, including estimates of the effect of synergy among the technologies on the overall capability. For example, the radionuclide tools in IVSEM are being used to explore different combinations of radionuclide stations that could have the initial xenon capability at the time of Treaty entry into force. Versions of the model have been released to selected DOE laboratories, U.S. government agencies, and contractors. IVSEM is being upgraded to incorporate capabilities such as the ability to easily include or exclude stations for study purposes and to model a satellite-based optical subsystem.



New capabilities for DOE's SAC2000 computer code include an interactive tool that improves the analyst's ability to detect and identify seismic phases. It allows users to pick phases and rotate signals (left), filter the data, interactively analyze three-component particle motions (center), and compute maximum-likelihood probabilities for selected wavetypes (right). The tool has helped solve problems such as incorrect sensor orientation.

Resolving Ambiguities: On-Site Inspections and Confidence-Building Measures



An inspection of the site of a suspect event must consider the time windows in which various nuclear explosion effects can be observed. The technologies developed by the DOE CTBT R&D Program are useful for gathering both short- and long-lived evidence.

If a State Party identifies an event that it feels could be a nuclear explosion, it can ask for consultation and clarification measures. Consultation and clarification measures simply ask for any information about the event that the State Party in whose area the event occurred might want to provide. If the requesting State Party is not satisfied with the information provided, it may send a request for an on-site inspection to the Executive Council of the CTBTO. The Council will consider the request and any accompanying data and vote to decide if the inspection should go forward. If the inspection is approved, international inspectors will carry out a suite of measurements on site to attempt to determine if the event was a nuclear test.

The United States has an interest in making sure that the international organization has the best technology, both equipment and interpretation algorithms, so that inspections are effective yet minimally intrusive. The Treaty also allows for confidence-building measures to help reduce the number of events that will require consultation and clarification or on-site inspection.

Technologies for On-Site Inspections

The Treaty specifies an extensive list of technologies allowable for on-site inspections. During the negotiations DOE contributed to the identification of appropriate technologies that now appear in the Treaty. Many of these technologies are mature and available. In addition, DOE conducted R&D in the following areas.

Aftershock Analysis. We showed that the low-frequency aftershocks associated with nuclear explosions also result from other types of events, such as mining collapses. These aftershocks are probably the result of blocks of rocks falling. Other techniques must be used in concert with aftershock analysis to declare that an event was nuclear.

Soil-Gas Analysis. Underground nuclear explosions produce radioactive xenon and argon soil gases. As part of our Non-Proliferation Experiment we found that tracer gases reach the surface after several months in some geologic conditions, and that this travel time may be estimated through calculations.

Plant-Stress Analysis. Underground explosions shock the ground immediately above the explosion; consequently, plants in this region may exhibit stress. Our results suggest that imagery can be used to detect plant stress.

During the PrepCom phase, DOE is contributing to development of procedures for use of these technologies under an on-site inspection.

Confidence-Building Technologies and Activities

The Treaty allows for information exchanges and on-site visits that can increase the States Parties' confidence that the Treaty's provisions are not being violated. Since these activities are voluntary, they constitute gestures of good will. States Parties are urged by the Treaty to notify the CTBTO Technical Secretariat about any planned chemical explosion of 300 tons or greater that is fired as a single explosion. Furthermore, the States Parties are urged to provide to the Technical Secretariat upon entry into force of the Treaty, and on an annual basis, the source time, location, and other pertinent information about the national use of such explosions. A State Party, in cooperation with the Technical Secretariat and other States Parties, may also carry out explosions for calibration purposes or it may invite observers to the site of large industrial explosions. During the PrepCom phase, the DOE is actively seeking partners for calibration explosions as well as an effective way of initiating the confidence-building-measures intent of the Treaty.

Source Characterization. At DOE we have developed technologies that can aid in the characterization of calibration explosions. For calibration explosions to be effective, their location and source time must be well known and their source characteristics carefully recorded. We have developed instrumentation that could serve this purpose. For example, we have integrated portable accelerometer stations with videocameras to establish zero time and to record the firing sequence of delay-fired mining explosions. We are also developing inexpensive, expendable accelerometer stations that could be left behind at mines that produce large-magnitude explosions to provide an independent record of explosion zero times.

Timeline:
CTBT History and Program Milestones

Evolution of the Treaty

Almost from the beginning of the nuclear age, the United States and other world powers have sought to bring about a Comprehensive Test Ban Treaty (CTBT). In March 1946 the United States released the Acheson–Lilienthal Report, which supported the creation of an international authority to control nuclear weapons and materials, and proposed the Baruch Plan to create such an authority; however, the plan was not adopted. In 1958, President Eisenhower proposed a Conference of Experts, later convened in Geneva, to examine CTB verification and began tripartite (United States, United Kingdom, and USSR) talks later in the year. U.S. experts, meanwhile, concluded that verification was more difficult than had been anticipated. This, combined with disagreements over the need for on-site inspections and other political factors, brought the talks to an end in 1959. From 1961 to 1976 interim steps to a CTBT were achieved in the Antarctic, Limited Test Ban, Outer Space, Latin America, Non-Proliferation, Threshold Test Ban, and Peaceful Nuclear Explosion treaties. The Limited Test Ban Treaty, which now has 117 parties, banned nuclear testing in all environments except underground. The Threshold Test Ban Treaty (United States and USSR) limited tests to 150 kilotons.

Attainment of a CTBT remained on the United Nations agenda and was pursued initially by the Eighteen-Nation Committee on Disarmament meeting under the auspices of the UN. This body evolved into the Conference of the Committee on Disarmament (CCD) and finally into the Conference on Disarmament (CD). In 1976, it created the *Ad Hoc* Group of Scientific Experts to Consider International Cooperative Measures to Detect and Identify Seismic Events (GSE). The GSE carried out three technical tests to evaluate CTBT monitoring concepts. When negotiations for a CTBT resumed in 1994, the CD created an *Ad Hoc* Committee for a Nuclear Test Ban (NTB) to do much of the work. The NTB held hearings on non-seismic monitoring means and convened its own panel of experts to recommend a monitoring concept. In the end, the NTB endorsed the third concept tested by the GSE and recommended that, besides seismic means, three other monitoring technologies be included in the CTBT monitoring system—hydroacoustic, infrasound, and radionuclide. The CTBT was adopted by the UN on September 10, 1996, and was signed by President Clinton and other heads of state on September 24, 1996.

To carry out its provisions, the Treaty establishes a Comprehensive Test Ban Treaty Organization (CTBTO) to be located in Vienna, Austria. The Conference of States Parties will be supported by an Executive Council, comprising 51 states serving on a rotating basis, that will have representatives from six regions: Africa; Eastern Europe; Latin America and the Caribbean; the Middle East and South Asia; North America and Western Europe; and Southeast Asia, the Pacific, and the Far East. Day-to-day operations of the CTBTO will be carried out by a Technical Secretariat headed by a Director General. On-site inspections and voluntary confidence-building measures are also coordinated by the Technical Secretariat. A Preparatory Commission is now in place, handling issues to get ready for Treaty entry into force; its Internet Web site (http://www.ctbto.org) offers information on the current status.

Monitoring: A Means of Verification

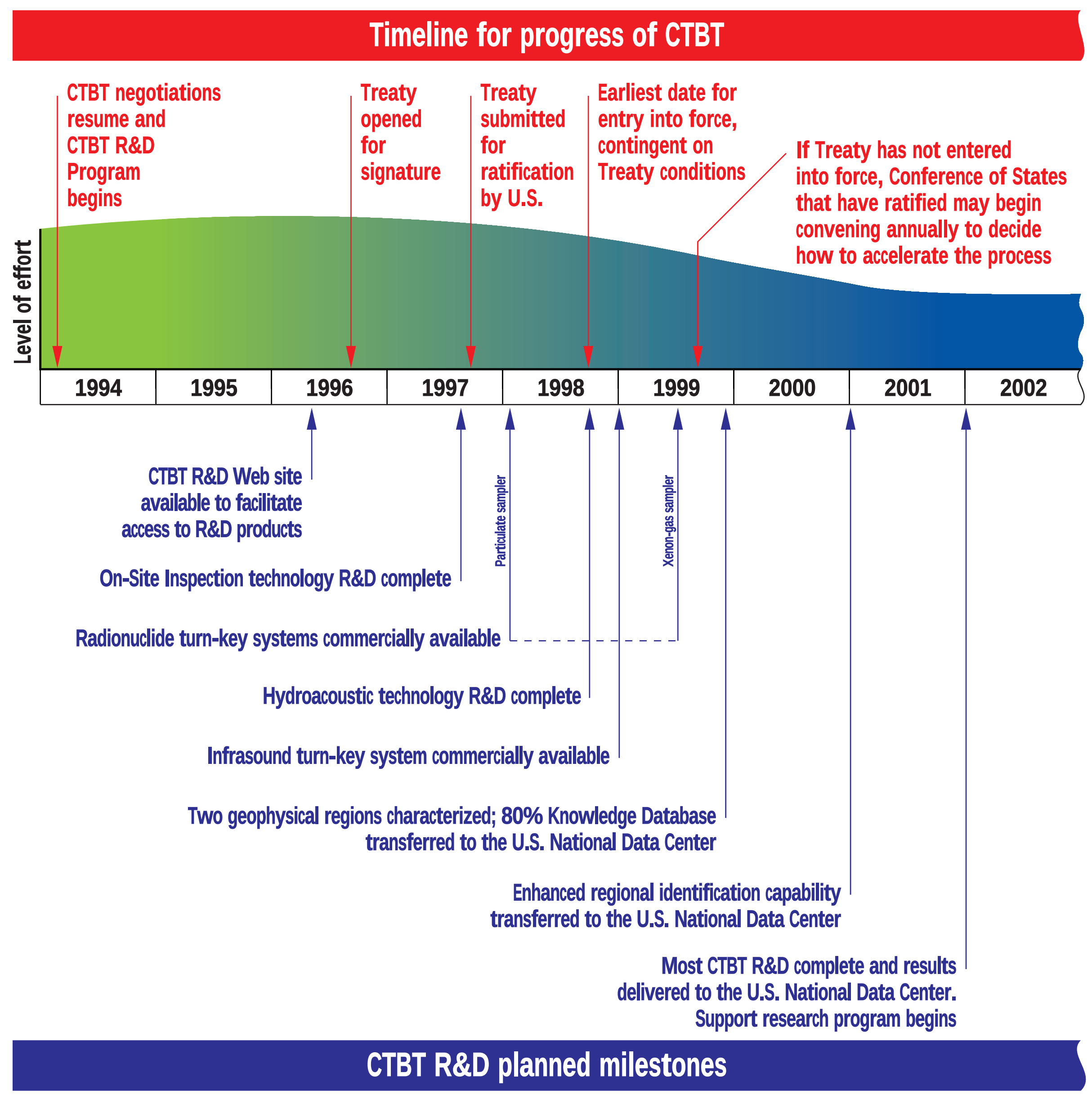
The major duties of the Technical Secretariat will be to coordinate the operations of the International Monitoring System (IMS) and to operate the International Data Centre (IDC). The existence of this global monitoring regime is intended to deter countries from conducting nuclear explosions in all environments (underground, in the oceans, and in the atmosphere) by providing considerable assurance to the international community that banned explosions will be detected.

The Three Phases of the Treaty

The first phase, the negotiations phase, ended with the opening of the Treaty for signing on September 24, 1996, at United Nations headquarters in New York. Signing the Treaty indicates a nation's intent to abide by its provisions pending ratification by its national law-making body. Any state that did not sign the Treaty initially may sign at any time. One hundred forty-nine nations had signed as of June 1, 1998.

After the Treaty was opened for signature, the ratification and Preparatory Commission (PrepCom) phase began. During this period, states ratify the Treaty while preparations are made for carrying out its provisions. This phase includes installing the monitoring stations, building the IDC, and installing communication links between the stations, the IDC, and States Parties.

The final phase is entry into force (EIF), which will occur 180 days after the date of deposit of Instruments of Ratification by the 44 states specified in Annex II of the Treaty but not earlier than two years after the Treaty was first opened for signature.



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