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Title: THE DEPARTMENT OF ENERGY'S COMPREHENSIVE TEST BANK TREATY RESEARCH AND DEVELOPMENT PROGRAM

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Nuclear Test Monitoring/ Infrasound/atmospheric explosions/ underground explosions/ ionospheric perturbations/ ionospheric hf sounding/ U.S. Department of Energy/ infrasound duct/

The U.S. DOE sponsored research investigating atmospheric infrasound as a means of detecting both atmospheric and underground nuclear tests. Various detection schemes were examined and were found to be effective for different situations. It has been discovered that an enhanced sensitivity is realizable for the very lowest frequency disturbances by detecting the infrasound at the top of the atmosphere using radio sound techniques. These techniques are compared to more traditional measurement schemes.

The Department of Energy's Comprehensive Test Ban Treaty Research and Development Program

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1. Introduction

The Department of Energy (DOE) is responsible for the United States Government's (USG) research and development functions for monitoring nuclear explosions in the context of a Comprehensive Test Ban Treaty (CTBT). This responsibility includes research and development for detecting, locating, identifying, and characterizing nuclear explosions in all environments.

This cooperative program draws upon the core competencies of the DOE national laboratories and upon the strengths of other U.S. Government agencies and the private sector (academia and industry). The integration of resources under a common direction should allow the program to develop and demonstrate appropriate technologies, algorithms, procedures, and integrated systems in a cost-effective and timely manner. The research addresses issues relevant to seismic, radionuclide, hydroacoustic and infrasound monitoring; on-site inspection; and automated data processing.

2. Background

Interest in the U.S. and the international community for reopening negotiations for a CTBT has been stimulated by the breakup of the Soviet Union, President Clinton's declaration of a U.S. moratorium on nuclear testing, Congressional legislation directing that a test ban be negotiated by 1996, and the upcoming extension conference for the NPT. The current CTBT negotiations began in January 1994. They are taking place in a multinational context where concern about both violations and confidence building exists. U.S. ratification of a CTBT will depend, in part, on the existence of a combined national and international monitoring system sufficient to meet its requirements for effective verification. In the discussions that follow we will distinguish between a global monitoring system (or regime) and an International Monitoring System (regime). The

International Monitoring System refers to that set of monitoring technologies which will be international constituted and openly shared between parties to the Comprehensive Test Ban Treaty. The global monitoring system will consist of the International Monitoring system and the National Technical Means of the various member states.

3. Operational Assumptions

The primary objectives of a global CTBT monitoring system are to deter nuclear explosions in all environments and, if such explosions do occur, to detect, identify, and attribute them to the proper source with high confidence. While technological progress over time should permit improvements in the quality of CTBT monitoring, high standards will be set from the outset in order to create a significant deterrent against those who may be tempted to carry out nuclear testing. The CTBT monitoring system should be able to

- Detect and identify nuclear explosions down to a few kilotons' yield or less, even when evasively conducted, and to do so in a timely manner.
- Provide credible evidence to the Treaty parties to aid in resolving ambiguities and to serve as the basis for collective or individual action.

A global CTBT monitoring system which monitors all environments would employ complementary technologies combined with on-site inspections and associated measures, e.g., exchanges of information. Interactive and mutually supportive technologies appropriate for use in an international monitoring regime include seismic, radionuclide sampling, hydroacoustics, infrasonics, and aircraft imagery. The various environments in which these technologies could generally operate are shown in Figure 1 and listed here.

Land : The primary asset for detecting explosions in the underground environment is the seismic network. A hydroacoustic system aids in the detection and identification of underground explosions in some specific circumstances by recording energy transmitted from the ground into the ocean.

Atmosphere : The primary technology proposed for an international monitoring system for identifying explosions in the atmosphere is a global radionuclide collection network. A global infrasound network is also under consideration to provide more timely detection and improved location accuracy.

Underwater : A global hydroacoustic system would detect underwater explosions and aid in event location. The seismic system would also detect and locate underwater explosions and aid identification.

Explosions near the surface of the land or the ocean can generate signals in both the ground and the air and the ocean and the air, respectively, and the above technologies in synergy will aid detection of the event.

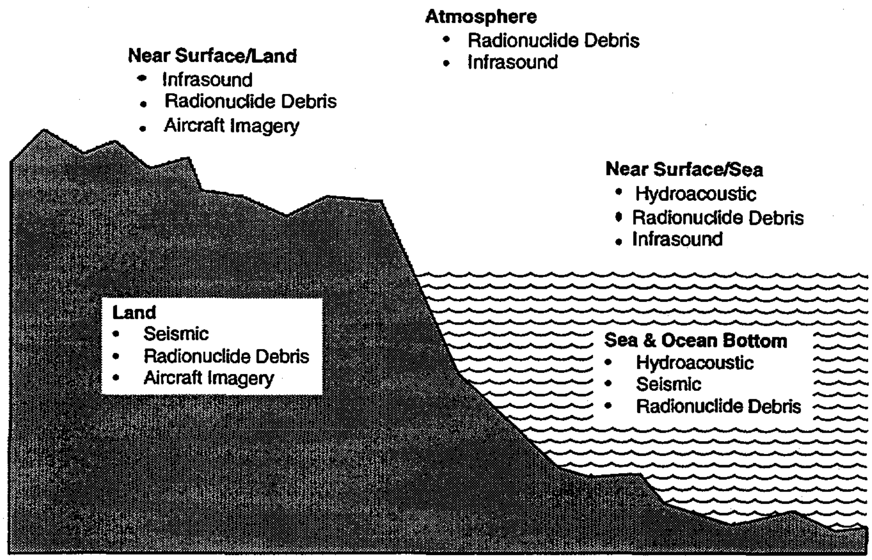

Figure 1. The above set of technologies are currently under discussion at the Conference on Disarmament for inclusion in an International Monitoring System.

Many factors will influence the choice of the technologies that will comprise the international monitoring system. System costs, monitoring effectiveness, availability of technologies, and potential false alarm rates are key factors currently being considered. It is anticipated that a limited range of technology will be negotiated and deployed. The DOE R&D program will be accordingly selective in its technology emphasis.

4. Technical Program Elements

In this paper we will outline the portions of the DOE's research program supporting the following elements: (1) seismic monitoring, (2) radionuclide atmospheric monitoring, (3) hydroacoustic monitoring, (4) infrasound monitoring, (5) on-site inspections, and (6) automated data processing. The research will attempt to embed these elements in a larger framework that addresses (1) efficient utilization of resources, (2) the usefulness of various technologies for identifying violations and avoiding false alarms in all environments, (3) the synergism achievable by forming a system that combines data from a variety of sensors with information available from other sources, and (4) the policy applications of the information generated by the monitoring system. The program will be coordinated with the efforts of other agencies with a role in CTBT monitoring and verification within the United States and with an international program as well.

A brief description of each of the elements of the program and a synopsis of the outstanding research issues follows.

4.1 SEISMIC MONITORING RESEARCH

The DOE seismic monitoring research will use both theory and the analysis of measurements made during controlled experiments and events-of-opportunity to develop methods that will improve the monitoring system's ability to detect, locate, identify and characterize seismic events. It will consider the monitoring challenges posed by nuclear explosions, conventional explosions, earthquakes, and rockbursts and will develop statistical measures of monitoring performance. While many of the basic uncertainty issues are common to both treaties, it is important to realize that the verification of a Comprehensive Test Ban Treaty presents the world with a qualitatively and quantitatively different problem from that posed by the regime of the Limited Test Ban Treaty. Verifying underground testing yields at 150 kilotons or greater permitted monitoring at inter-continental distances (teleseismic wave propagation). Detection, location and identification of significantly smaller events (a few kilotons or less) of necessity requires monitoring distances of the order of two thousand kilometers or less (regional distances). As depicted schematically in figure 2, regional waves propagate in the upper mantle and heterogeneous crust introducing problems of velocity uncertainty and directional scattering which must be dealt with in the context of a significantly larger set of events that may have some characteristics similar to those of nuclear explosions. These events may range from earthquakes to mining and quarrying explosions to rockbursts and mine collapses.

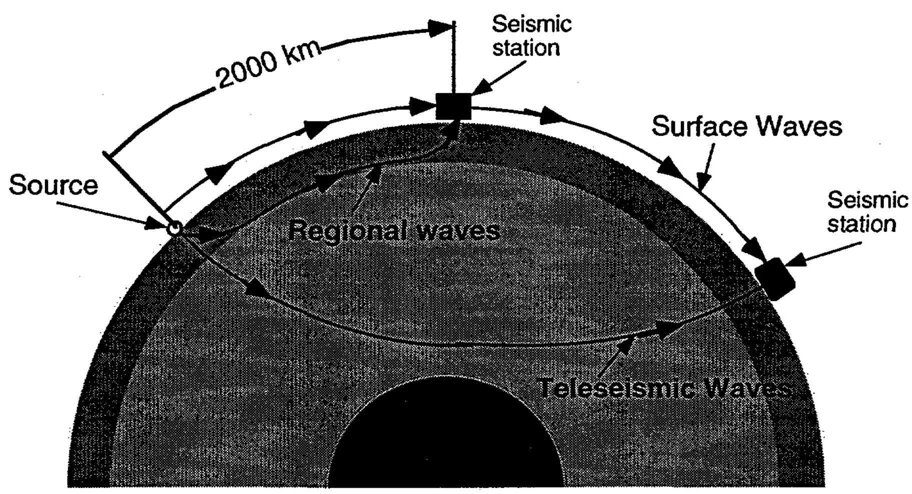

Figure 2. Regional monitoring for small events requires the detection of regional rather than teleseismic waves. The propagation of regional waves principally through the Earth's crust gives rise to location inaccuracies which as less pronounced for teleseismic waves.

Efficient methods must be developed to discriminate between these potentially troublesome sources and nuclear tests. Figure 3 illustrates the potential magnitude of the discrimination problem. There are many tens of thousands of such events annually on the global scale.

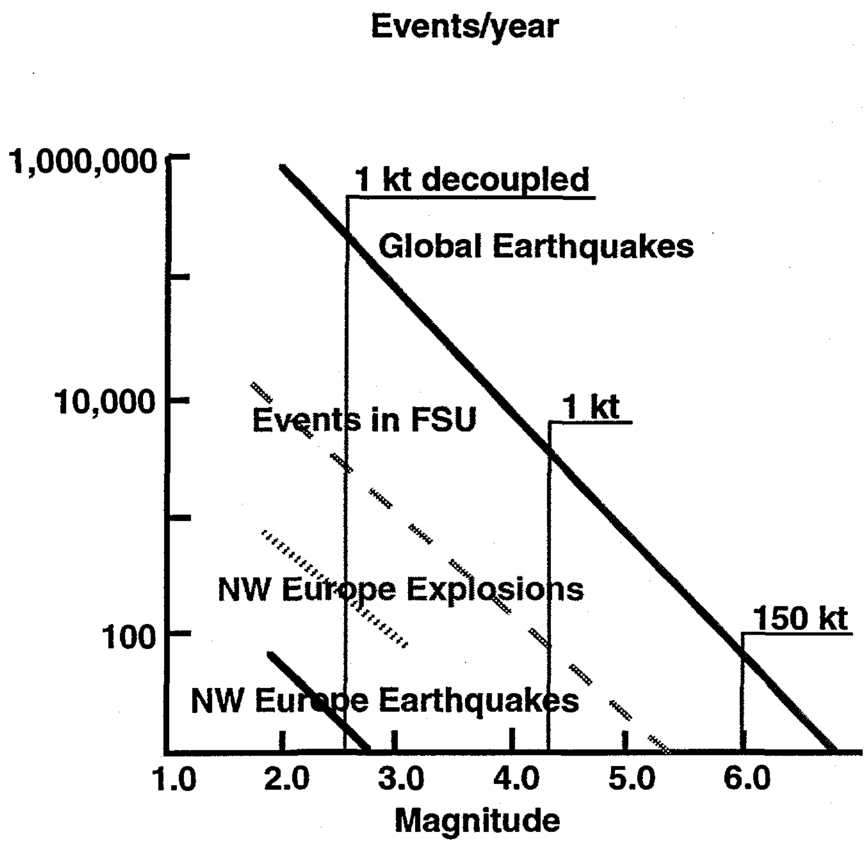

Figure 3. The above graph demonstrates that the lowering of detection thresholds introduces many more events annually that must be discriminated from potential nuclear explosions.

The DOE seismic research will examine several facets of this problem. It will undertake the problem of developing regional discriminants in several areas of the world. Decoupling will be examined in the context of the effects of cavity size, shape, and emplacement material on the regional seismic signals. Various mining and industrial activities will be thoroughly examined in order to develop confidence building measures and study the problem of potential masking of signals from nuclear explosions. Since many regions of the world will require calibration for the effects of propagation on regional phases the research will develop a characterization methodology to be applied from region to region in a more or less routine manner.

Our emphasis will be regional throughout the research. Regional propagation preserves a wider band of frequencies between source and sensor allowing the use of a relatively wide bandwidth to examine various discrimination algorithms. In the important case of earthquakes, accurate determination of depth will permit the immediate exclusion of events that are too deep to be reasonable for evasive testing. Since this depth limit is on the order of one kilometer, location accuracy on the order of one kilometer will be our objective although we suspect that it is unlikely to be achievable within reasonable costs. Even accuracy on the order of 5 kilometers will only be realized with very detailed characterization of the seismic wave propagation properties of specific regions of interest. The research will attempt to develop statistically significant improvements in event characterization, find solutions to the monitoring challenge posed by conventional explosions and identify the critical factors affecting monitoring performance in each new region of interest.

4.2 RADIONUCLIDE ATMOSPHERIC MONITORING RESEARCH

Radionuclide atmospheric monitoring research will address real-time detection and analysis of noble gases and particulate debris from nuclear testing. The program will provide the instrumentation systems necessary to identify atmospheric and subsurface nuclear explosions that vent into the atmosphere. This equipment will be suitable for international deployment. It will look to improvements in sensitivity levels provided by real-time radionuclide monitoring instrumentation instead of sample collection and laboratory analysis, and will address fieldability of radionuclide monitoring instrumentation by enhancing ruggedness, reliability, weight, and power usage.

4.3 INFRASOUND ATMOSPHERIC MONITORING

Infrasound has long been recognized as a useful technique for detecting and locating atmospheric, shallow buried or partially submerged nuclear explosions. It supplements radionuclide monitoring by providing rapid reporting within hours rather than days and it provides a reasonably accurate event location within about 100 kilometers with a very low false event rate. The International Monitoring System might use arrays of microbarographs and infrasound microphones.

The DOE program will be addressing outstanding research issues which will be useful in determining the design and function of a potential infrasound system for global monitoring. From existing models of atmospheric propagation of infrasound, global detection capability will be estimated as a function of source size, number, and distribution of stations and background noise levels. Various array configurations will also be examined for the most cost effective solution to system design.

4.4 HYDROACOUSTIC MONITORING RESEARCH

The goal of DOE's hydroacoustic monitoring research will develop techniques, specifications and (possibly) prototype hardware for a hydroacoustic system that detects, locates and identifies nuclear detonations in, on or above the oceans.

The research has three major components: (1) a numerical modeling effort to determine nuclear test signatures, estimate worldwide hydroacoustic coverage, and examine interactions with other technologies; (2) an empirical effort to verify the calculations; and if necessary, (3) an engineering effort to specify and prototype a low-cost hydroacoustic system. These three program components are described below in more detail.

In support of (1), the DOE plans to assemble the necessary nonlinear propagation models and oceanographic databases to characterize propagation in the world's oceans. We propose to calculate estimates of the long-range nuclear signature and of propagation loss in areas of interest. In addition, the research will address the coupling of near-surface and deep explosion energy to seismic paths, and the combined use of hydroacoustic and seismic assets for event discrimination.

DOE proposes an empirical effort (2) to validate propagation codes and results obtained by using recordings of explosions of opportunity as well as historical data. In one approach, the pattern of observed/missed T phases from undersea earthquakes and other sources of opportunity will validate theoretical estimates of attenuation in shallow seas and bathymetric shadowing.

DOE plans first to specify the desired system characteristics based on modeling results and then, if warranted, proceed to (3) prototype development. DOE will evaluate vertical hydrophone arrays suspended beneath free-drifting and moored buoys, bottom-mounted hydrophone arrays cabled to shore and other configurations for possible modification for the nuclear test surveillance task. The DOE may select an existing system, perform the engineering modifications, test the prototype, and develop a deployment plan for the numbers and locations of sensors needed to meet CTBT monitoring needs.

4.5 ON-SITE INSPECTION RESEARCH

An on-site inspection (OSI) is an in-person visit to a site to collect data and evidence in order to determine the source of an ambiguous event detected via remote monitoring systems or other measures. Its purpose is to determine if the treaty has been violated, deter violations, and build confidence. On-site inspections could occur in two different contexts: after-the-fact inspections based on information from remote monitoring systems and inspections prior to, during, and after large, declared chemical explosions (for example a large mining explosion).

OSI monitoring techniques should detect the phenomena and residual effects of nuclear explosions. The primary effects from underground explosions that are of interest for OSI's are the electromagnetic pulse, shock waves, aftershocks, radioactive gas, rubble zone, and apical void (figure 4). These effects are well known and the basic techniques for their detection well established. We designed our research to answer specific performance issues about these detection technologies. Our research includes emphasis on zero time electromagnetic and accelerometer measurements, aftershocks, radioactive gas sampling, multispectral overhead imagery, and visual surveys.

A rough guess for the error estimate of the event location from the remote monitoring system is approximately 1000 sq. km. A key issue is the reduction of this region to approximately 100 sq. km. so that aftershock detection is feasible. Overhead imagery could assist in the process. Simple visual inspection could be used to look for

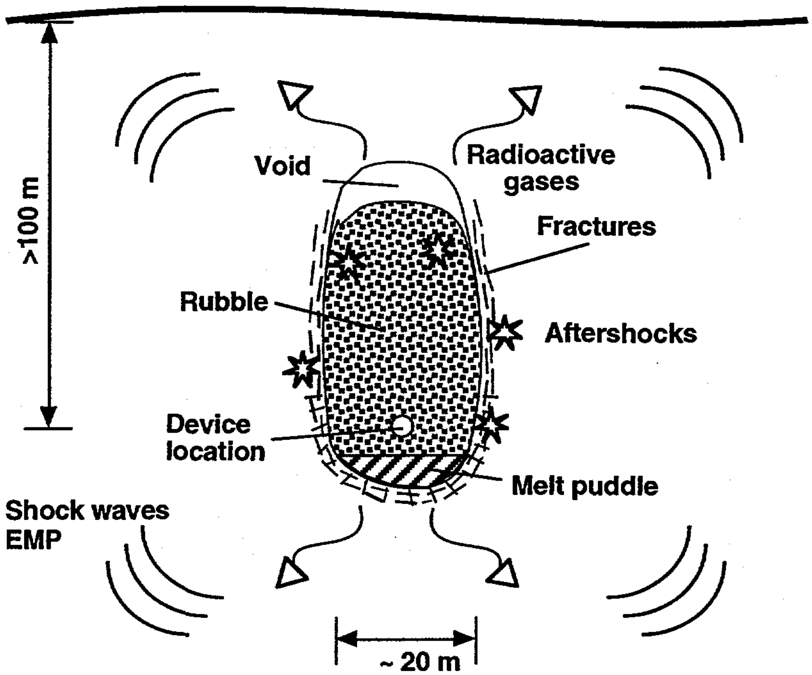

Figure 4. The cartoon above depicts the underground environs of a recently detonated nuclear explosion with some indications of potential size scales.

recent activity such as new roads and evidence of drilling. If the ground zero of a nuclear explosion does not collapse, it is still likely that it underwent spallation. Plants growing in the region could be stressed through breakage of root hairs and other means. If the region is bare ground, the spallation could change the surface reflectance properties. We are using high-resolution low-altitude imagery data to attempt to develop techniques for detecting this spalled region.

Once a subregion has been chosen, aftershocks monitoring could be used to narrow the region even further, to approximately 10 sq. km. Since aftershock production falls off rapidly with time and the inspection team may not be in the field until several weeks after the event, the inspection team may record only a few after shocks. There is a suggestion from previous Nevada Test Site events that some explosion aftershocks have anomalously low frequency compared to earthquake aftershocks. We are investigating the occurrence of these low-frequency events to determine if they are associated with other processes such as mining.

Once the search has been narrowed down to a few square kilometers, the inspectors may try to collect a radioactive sample from the detonation point. An obvious way is to drill and retrieve a core sample. Drilling in remote locations is expensive and is hazardous if a radioactive zone is encountered. Because of the difficulty and expense of drilling a more likely first attempt is taking gas samples to collect radioactive gases.

These gases could require many months to seep out of the ground if the explosion was well contained. Local barometric pressure plays a role since gas flows into and out of the ground during periods of atmospheric lows and highs. We are investigating the role of atmospheric pressure and pressure driven flow from the explosion to design optimal gas sampling strategies.

For monitoring large chemical explosions at zero time, electromagnetic pulse monitoring offers a possible discriminant between nuclear and chemical explosions. We are investigating the source of the magnetic pulse for nuclear and chemical explosions. Monitoring of the strong ground motion in the local region around a shot may locate a nearby clandestine explosion. We are investigating methods to separate the signals of closely spaced nearby simultaneously detonated explosions.

4.6 AUTOMATED DATA PROCESSING RESEARCH

Automated data processing research will provide the significant data processing improvements (e.g., processing very large volumes of data) necessary to automatically and reliably detect, locate, identify and characterize nuclear events. The program will develop software tools which will support the research carried out by the rest of the program. It will emphasize automating the seismic monitoring task to process the expected significant increase of events to be examined. The developments from the program should enhance the GSETT-3 (Group of Scientific Experts Technical Test) International Data Center/National Data Center's ability to scan automatically and to reliably acquire data from the global seismic network and use that data to detect, locate, and characterize global seismic events in a real-time fashion. We are looking to enhance detection, location, and identification; location accuracy; depth accuracy; false alarm rate; confidence factor associated with identifications; and the ability to operate in real time. Some specific goals for the near future include the development of automated detection and location algorithms using the full seismic waveforms, development of automated processing software with the capacity to handle greatly enhanced volumes of data required for the global CTBT monitoring task, an analysis of problem and a proposed solution of authentication and security of data within the International Monitoring System, and the development of software for acquiring and integrating multi-source data. Our overall aim will be to keep the requirement for human operators to a minimum while demonstrating techniques for improving the whole analysis environment.

It is our intention that the products of the CTBT R&D program will be major factors in ensuring that U.S. CTBT monitoring goals will be achieved within cost constraints. DOE, in its management role of the CTBT R&D program, will coordinate the CTBT R&D efforts with the US interagency verification community to assure that the program addresses the community consensus view of these goals. To this end, DOE will hold informal and regularly scheduled formal meetings with the community. These meetings will help shape the DOE program in the context of dynamic policy and technical developments. In addition, the meetings will keep other agencies informed of the status of the evolving DOE program. To ensure that the technical aspects of the program are proceeding in an appropriate manner, DOE will also seek continuing input from various elements of the technical community (e.g., contractors, university personnel, and others).

Although DOE has been assigned the primary responsibility within the United States for research and development functions in support of monitoring nuclear explosions, other agencies and organizations, both domestic and foreign, have resources that can contribute to both national and international monitoring capabilities. DOE's program will place a high priority on coordinating these resources in order to avoid duplication and ensure full utilization of results.

5. Summary

DOE has been given the responsibility for the research and development essential to provide the US agencies responsible for monitoring compliance with a CTBT with the integrated systems necessary to detect, locate, identify, and characterize nuclear explosions. Successful fulfillment of this responsibility will also increase confidence in the performance of the monitoring system by reducing the number of false alarms to the lowest level consistent with effective detection of treaty violations. The program will focus on seismic, radionuclide, ocean, on-site inspection monitoring, infrasound and automated data processing technologies.

In order to address these responsibilities, DOE and its National Laboratories have committed themselves to a cooperative, structured program that draws upon the core competencies of each DOE organization; the strengths of other agencies and the private sector; and frequent interaction with end users. The integration of resources and ties to the users will allow the program to develop and demonstrate effective monitoring technologies, algorithms, procedures, and integrated systems in a cost-effective and timely manner. The introduction of a formal, multi-laboratory structure for program management will support integrated system development, provide a means for evaluating the costs and benefits of current developments and future improvements, and facilitate interaction with the agencies responsible for monitoring nuclear testing and verifying compliance with a CTBT.