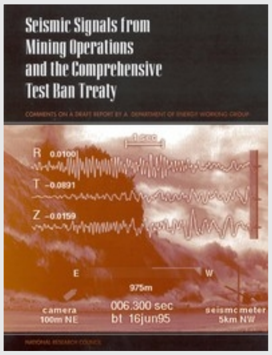

Seismic Signals from Mining Operations and the Comprehensive Test Ban Treaty: Comments on a Draft Report by a Department of Energy Working Group

DETAILS

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Seismic Signals from Mining Operations and the Comprehensive Test Ban Treaty

Comments On A Draft Report By A Department Of Energy Working Group

Committee on Seismic Signals from Mining Activities
Board on Earth Sciences and Resources
Commission on Geosciences, Environment, and Resources
National Research Council

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Cover: Video image taken 6.300 seconds into a large cast shot at the Black Thunder coal mine in Wyoming. Superimposed on the image are traces of the radial (R), transverse (T), and vertical (Z) velocities recorded 5 km from the blast. The vertical bar at the right side of the traces is at 6.3 seconds after the beginning of the shot. The three-component particle velocity is represented in the lower right-hand corner. Figure courtesy of Brian Stump and David Anderson, both at Southern Methodist University, Dallas, Texas.

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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making their published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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While the individuals listed above have provided many constructive suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Preface

In 1996, the Department of Energy's (DOE) Office of Non-Proliferation and National Security organized a working group to synthesize the results of a research program that addressed the nature of seismic signals from mining operations and whether such signals might be of concern to monitoring and compliance of the recently negotiated Comprehensive Test Ban Treaty (CTBT). A number of mining-related seismic signals were detectable or visible to the International Monitoring System, which was being developed for the treaty. As such, the DOE Working Group considered measures that could help reduce the visibility of mining-related seismic signals and ways of distinguishing between seismic signals emanating from natural earthquakes, nuclear tests, and legitimate mining operations. The DOE Working Group was co-chaired by François Heuze (Lawrence Livermore National Laboratory) and Brian W. Stump (Los Alamos National Laboratory). In March 1997, the DOE Working Group issued a draft report and recommendations entitled *Reducing the Ambiguity and Visibility of Seismic Signals from Mining Activities: Benefits to the Mining Industries and to the Communities Monitoring the Comprehensive Test Ban Treaty (CTBT).*

That same month (March 1997), the DOE's Office of Non-Proliferation and National Security requested that the National Research Council (NRC) undertake a study to review the draft report. The request specifically asked the NRC committee to address the following questions in its charge:

(1) Are the recommendations scientifically valid?
(2) Would the recommendations result in reduced seismic visibility if implemented?
(3) Are there additional practices that would reduce the ambiguity and visibility of seismic signals from mine-related events?
(4) How should the recommendations be disseminated to the mining community to promote their use in mine engineering practice?

To draw upon the expertise and experience of several relevant NRC units, the scope and nature of the study was discussed by the NRC's Board on Earth Sciences and Resources and three of its committees. The Committee on Seismology recently completed two reports relevant to the CTBT and has been involved in issues of seismic monitoring of nuclear explosions for over 30 years. The Committee on Earth Resources focuses on energy and mineral resource issues and has expertise in mining. And finally, the U.S. National Committee for Rock Mechanics has expertise in geomechanics, blasting, and ground failures. The proposed study also was discussed by the Board on Energy and Environmental Systems. These discussions were useful in informing these committees about the study, obtaining input from leading experts in several key disciplines, and obtaining suggestions for potential committee members.

The Committee on Mine Seismicity and the Comprehensive Test Ban Treaty was appointed by the chairman of the NRC in November 1997. In January 1998, the committee met and held open discussions with four of the DOE Working Group members and a representative of DOE's Office of Non-Proliferation and National Security. In February 1998, the committee met again to prepare the report; consensus was readily achieved.

Contents

Executive Summary

The Comprehensive Test Ban Treaty (CTBT) has been signed by 149 nations and bans all nuclear explosions. As of May 1998, the U.S. Senate has yet to ratify the treaty. A global seismic network forms part of the basis of the International Monitoring System (IMS) being established for CTBT compliance. The seismic magnitudes of a small number of mining explosions can be similar in size to those resulting from a small or decoupled nuclear explosion. Mine collapses or rockbursts can also generate similar-sized seismic signals. Not only would some mining-related seismic signals be detectable by (visible to) the IMS, but also some could potentially be misinterpreted as nuclear events and treaty violations.

The Department of Energy (DOE) convened a working group that prepared a draft report, *Reducing the Ambiguity and Visibility of Seismic Signals from Mining Activities,* in March 1997 (that Executive Summary is in Appendix B). DOE asked the National Research Council (NRC) to conduct a review of the working group's report. That review is the subject of this NRC study. The DOE Working Group approached its topic primarily from a perspective of decreasing the size (i.e., visibility) of seismic signals resulting from mining operations. Within this context, their report suggested several changes in blasting and mining engineering practices. These included decreasing the amount of explosives used in each shot of a multishot blasting sequence and reducing the diameter of the boreholes, which contain the explosives, in the blasting pattern. The changes suggested by the DOE Working Group are technologically feasible and would result in decreased magnitudes of the seismic signals. The DOE Working Group report, however, did not evaluate whether the suggested changes were pragmatic and could be implemented by the mining industry. The NRC's review committee concludes that the cost of implementing the suggested changes could affect the viability of a mine in a highly competitive international environment. Because of this economic concern, **the NRC committee recommends that emphasis be given to improving monitoring capabilities to decrease the ambiguity of seismic signals from mining operations,** rather than relying on efforts to alter blasting and mining engineering approaches. The DOE Working Group acknowledged the value of monitoring approaches, but placed greater emphasis on decreasing the visibility of seismic signals.

A majority of mining-induced seismic signals, including those resulting from all blasting at most mines, would be invisible to the CTBT monitoring network because of their small size. Among those signals that are visible to the IMS, most could be clearly associated with legitimate mining activities by a voluntary characterization program, thus substantially reducing any ambiguity. Mining operations that use large explosive yields—that is, greater than the 300 metric tons TNT-equivalent specified in the treaty—could voluntarily submit the time and locations of a few of their larger blasts to the agency (not yet specified) responsible for U.S. CTBT compliance. The resulting data could lead to improved travel-time models and corrections that would enable very accurate locations for signals originating at or near those "calibrated" mines. This ability would greatly reduce the ambiguity of many small seismic signals detected by the CTBT seismic monitoring system and would make it possible to rapidly obtain confidence-building information from the mine to explain any questionable signals. For the very few mines that might emit large signals that are still ambiguous despite the process described above, mine operators may want to take more active voluntary measures and allow installation of an unintrusive, on-site monitoring system such as that discussed in the DOE Working Group report. The benefit to the mining companies would be the avoidance of possible international CTBT on-site inspections of legitimate mining activities.

Seismic signals originating from rock bursts, coal bumps, or mine collapses are more likely to be ambiguous than those originating from blasting operations. For mining operations that had significant geologic events that might generate observable seismic signals, it would be extremely useful for treaty monitoring if these operations would report the location and approximate time of these events. However, this is not included as one of the voluntary measures within the treaty,

The burden of the above measures to decrease ambiguity of seismic signals should not be onerous to the mining community. The NRC review committee believes that U.S. industry cooperation in this important national initiative will be forthcoming.

Such a voluntary approach to decreasing the ambiguity of seismic signals originating from mining operations within the United States could set a positive example for other countries to participate in confidence-building measures under the treaty regime.

1

Introduction

CTBT GOALS

As of January 1998, the Comprehensive Test Ban Treaty (CTBT) banning all nuclear explosions has been negotiated and signed by 149 countries, including the United States (India, Pakistan, and North Korea were not signatories). By the Law of Treaties, the signatories are bound to abide by the provisions of the CTBT prior to its entry into force, effectively creating an immediate moratorium on nuclear weapons testing. As of May 1998, the U.S. Senate has yet to ratify the CTBT. Verification of compliance with the CTBT will be a major concern of many nations in both the short and the long term. Compliance will require a concerted effort to enhance capabilities to identify violations, minimize false alarms, and thus maintain confidence.

The technical systems put in place to monitor the CTBT will be employed to detect, locate, and identify small "events" underground, underwater, and in the atmosphere with high confidence and accuracy. As stated in a 1997 NRC report[1], the present monitoring systems will not detect with high confidence very low-yield tests. President Clinton[2] stated that the CTBT goal for the United States is to be able to detect "a few kilotons evasively tested" in selected areas of the world. Evasive testing involves masking or muting the signals from a nuclear explosion (detonation in a large cavity can significantly reduce the magnitude of seismic signals, for example), although other CTBT monitoring techniques might still be able to detect evasive tests.

[1] *Research Required to Support Comprehensive Nuclear Test Ban Treaty Monitoring,* Committee on Seismology, Board on Earth Sciences and Resources, National Research Council, p. 2.

[2] White House Press Release, August 11, 1995.

CTBT MONITORING METHODS

An International Monitoring System (IMS) will be established for monitoring compliance of the CTBT. A major component of the IMS is a worldwide network of seismic stations. Seismic signals that will be detectable by (visible to) the IMS will originate from both natural and man-made sources; an IMS goal is to be able to detect events with a magnitude of about 3.0 (M_b). Naturally occurring events include earthquakes and volcanic eruptions, most of which are deeper than man-made seismic sources. Accurate locations of such events to hypocentral depths greater than 10 kilometers makes further consideration of these events unnecessary in the context of monitoring compliance. More enigmatic from the monitoring perspective are man-made or induced seismic signals resulting from (1) applications using conventional explosives for mining and excavation, and (2) rock bursts and collapses associated with surface or underground mining operations. The seismic magnitudes of a small number of mining explosions can be similar in size to those resulting from a small or decoupled nuclear explosion. Mine collapses or rock bursts can also generate similar-sized seismic signals. Uncertainties in the seismically determined location[3] of such an event may not allow assignment of an event to a specific mine unless local data are available. By itself, determination of location may not be sufficient to identify the source type, and event identification will need to rely on distinguishing features of the seismic wave forms, possibly in conjunction with other monitoring technologies. Of the other monitoring technologies to be used by the IMS, infrasonics or detection of atmospheric signals are the most germane to monitoring explosions from mining operations.

Recognizing that mining blasts represent a significant source of small-magnitude seismic signals, the CTBT calls for voluntary exchanges of information on large mining explosions as part of the treaty's confidence-building measures. These include annual surveys to determine which mines in each country detonate explosives over 300 metric tons (TNT-equivalent), notifications of blasts in which 300 metric tons or more of explosives are detonated in a single explosion[4], and dedicated calibration explosions. These measures, although voluntary and not mandated by the treaty, could significantly improve the performance of the monitoring system and reduce the *ambiguity* of some mine-related seismic signals by allowing for the identification and calibration of mine event locations and signal types.

[3] A discussion of locational errors associated with seismic sources is given in Appendix C of the 1997 NRC report, *Research Required to Support Comprehensive Nuclear Test Ban Treaty Monitoring.*

[4] The section of the CTBT dealing with confidence-building measures does not explicitly differentiate between one single explosion and a delay-fired blast where hundreds of boreholes filled with explosives may be detonated in a sequence within a few seconds. The largest delayed-fired blast (Powder River Basin, Wyoming) detonated about 3,600 metric tons of explosives over a 4- or 5-second period.

MINING ACTIVITIES THAT GENERATE SEISMIC SIGNALS

Mining activities can produce a wide variety of induced ground motions, including seismicity. At the mine site and the surrounding areas, blasting produces local vibrations though mine operators and explosives engineers strive to minimize many of the effects of these vibrations by careful blasting designs. In some cases, ground motions or seismic waves, may be detected at long distances (hundreds of kilometers) from the mine site (see Figure 1). The sources of these seismic signals include (1) surface and underground mine blasting that use large quantities of explosives and (2) the planned or unplanned failure of masses of rock that release a large amount of energy (e.g., rock bursts, coal bumps, planned roof collapses, pillar collapses, and other rock failures).

Seismic waves generated from mining activities are sometimes detected by regional seismograph stations that also monitor and record earthquakes. Seismograms recorded for earthquakes and nuclear blasts can have characteristics that permit discriminating the type of event (see Figure 2). A simultaneously detonated chemical explosion can generate a ground motion-time history (see Figure 3) that is similar to one generated by a nuclear blast.[5] The similar characteristics include wave form amplitude, frequency, spectral content, and duration.

Current seismological instrumentation and the methods used to process and analyze seismic signals are not always capable of discriminating between certain mine-induced seismic signals and explosions resembling nuclear blasts. Hence, some mining activities can produce seismic signals that could possibly be mistaken for clandestine nuclear blasts.

AMBIGUITY AND ON-SITE INSPECTIONS

Experience suggests that most seismic signals that generate suspicion will probably be either anomalous shallow earthquakes, mine collapses, or large mining blasts that occur at the surface or underground. Under the terms of the treaty, an event detected by at least three of the primary stations of the IMS should be reported in the seismic bulletin to be published by the international CTBT organization. Events generating signals that cannot be readily explained as generated by known mining activities might initiate a request for an on-site inspection (OSI) by an international team of experts seeking to verify or deny the occurrence of a nuclear explosion. It is anticipated that on-site inspections will be rare. Mining operators could help reduce false alarms under the treaty by providing information on large mining blasts they generate. The ambiguity of seismic signals generated by mining

[5] Kim, Simpson, and Richards (1994, High-Frequency Spectra of Regional Phases from Earthquakes and Chemical Explosions, *Bulletin of the Seismological Society of America 84,* pp. 1365–1386) noted that spectra of ripple-fired shots (delayed fired shots to the blasting engineers) have systematic patterns of constructive and destructive interference, presumably caused by signals from the individual shots in the ripple-fired set interfering with each other. Also there is a strong, impulsive, P-wave arriving from the single shot that is greatly reduced for the ripple-fired shot.

activities would be lessened by efforts to (1) identify the signal sources and (2) determine the seismic character of those events. Alternatively, mining operations could become less seismically visible by modifying their procedures to send out smaller amplitude seismic signals.

A robust international effort to reduce ambiguity would also aid U.S. monitoring agencies in their efforts to ensure world-wide compliance with the CTBT. A strong effort by the U.S. mining industry to reduce ambiguity would put the United States in a good position to offer technical support to other nations and to the CTBT Organization (CTBTO) so that other nations may more easily follow the U.S. example.

Should a nation be suspicious of a seismic signal, it may take either bilateral or “consultation and clarification” steps to resolve its suspicions before attempting to persuade the CTBTO to carry out an on-site inspection. If the requesting nation selects bilateral measures, then it may simply contact the other nation and ask for an exchange of information and perhaps of scientists and engineers. If the nation instead chooses consultation and clarification, then it may ask the CTBTO to obtain clarification from the “requested state party,” whose response is required within 48 hours. If the response is unsatisfactory to the requesting nation, it may request a meeting of the Executive Council of the CTBTO to consider appropriate action and perhaps an on-site inspection. The latter requires approval of 30 of the 51 member nations on the Executive Council.

The committee believes because of the established procedures provided by the treaty leading to an OSI and the opportunities to explain ambiguous events with data, that on-site inspections will probably be rare in the United States. For an average mine, the probability of an OSI during the mine's operational life is very low. Furthermore, for a mine with no clandestine activity—presumably the case for U.S. mines—the committee believes that an OSI probably would not be overly intrusive and probably would not require shutting down mine production.

GOALS OF DOE WORKING GROUP REPORT

Because mining activities worldwide can generate seismic signals that may in rare cases appear as prohibited nuclear explosions, the seismic signals generated by mining may become *visible* to seismic monitoring activities that are part of the CTBT. A stated goal of the DOE Working Group's[6] draft report, *Reducing the Ambiguity and Visibility of Seismic Signals from Mining Activities,* is to identify

[6] The Working Group convened by the Department of Energy's Office of Non-Proliferation and National Security was co-chaired by François Heuze (Lawrence Livermore National Laboratory) and Brian Stump (Los Alamos National Laboratory). Other members were Frank Chiappetta (Blasting Analysis International), Robert Hopler (Powderman Consulting, Inc.), Vindell Hsu (Air Force Technical Applications Center), Bob Martin (Thunder Basin Coal Co.), Craig Pearson (Los Alamos National Laboratory), William Walter (Lawrence Livermore National Laboratory), and Karl Zipf (Mine Safety and Health Administration).

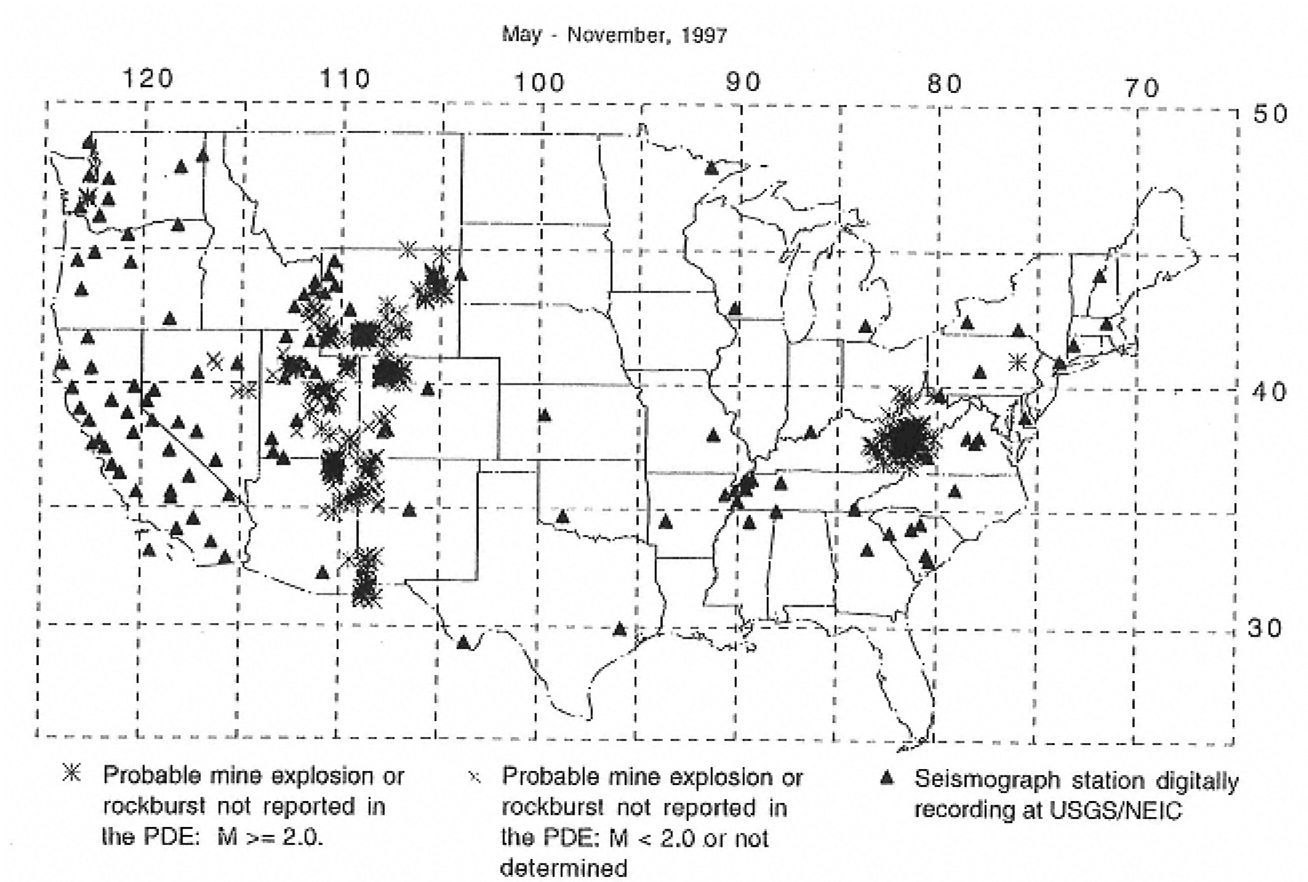

Figure 1. Seismic signals generated by mining operations in the United States that are detectable by the national network for the period May through November 1997. Of the 956 events located on the map, 237 had a local or regional magnitude of 2.5 or greater (~25%), of which 55 had a magnitude of 3.0 or greater. There were two events with a magnitude greater than 3.5 (both at 3.6). As such, most signals probably would not be visible to the International Monitoring System for the CTBT (a bried discussion of magnitude measures can be found at the end of Appendix A. The map was compiled by the National Earthquake Information Center of the U.S. Geological Survey; data, bulletins, explanations, and other maps can be found at http://earthquake.usgs.gov/neis/mineblast/.

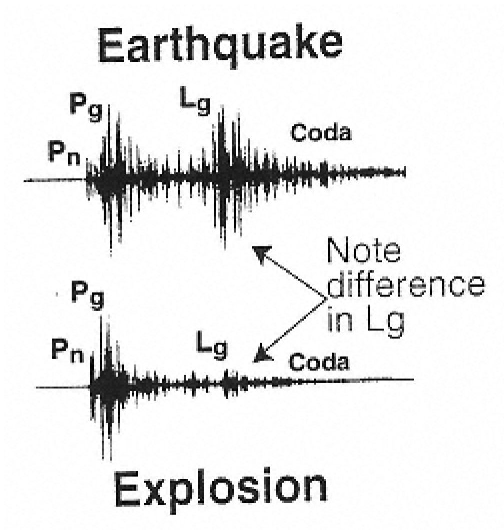

Figure 2. Seismograms (recorded at the same station) generated by an earthquake and an explosion near the Nevada Test Site. Both are filtered to emphasize the high frequencies (6–8 Hz); differences in amplitude of L_g waves clearly distinguish the two events. Adapted from Walter, 1996 (Lawrence Livermore National Laboratory, UCRL-MI-123958), and from Figure 1.B.2. of the DOE Working Group draft report).

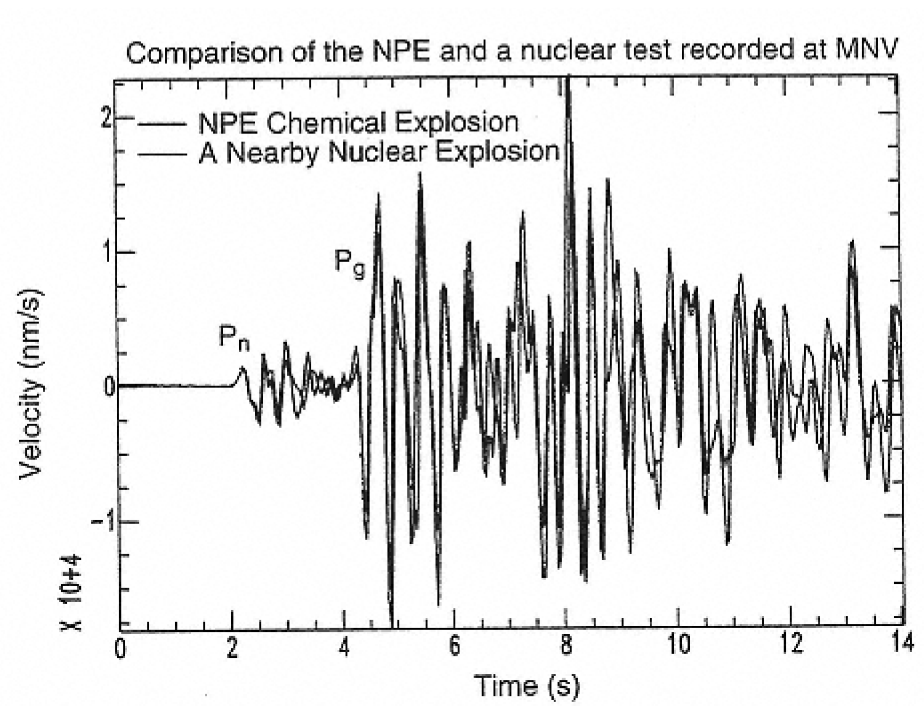

Figure 3. Comparison of the P energy at regional distance (same station) from a large single chemical explosion (non-proliferation experiment) and a near-by nuclear explosion (named Hunters Trophy). From Figure 2.B.1. of the DOE Working Group draft report. Similarities are striking. However, the NPE is not necessarily representative of chemical explosions detonated by the mining industry.

those mining "practices and tools which…would likely reduce the false alarms that may be registered by an International Monitoring System."

The DOE Working Group report reviews seismic sources associated with mining operations and some recent research intended to help characterize the signals generated by these sources nearby and at regional distances. The report then considers how (1) the size of the regional signals might be reduced, or (2) the resulting signals could be more easily recognizable as mining related.

The DOE Working Group report states that the "U.S. mining industry is intended to be the primary beneficiary of this work. If the mining practices recommended…are adopted by the mining companies, they will likely provide intrinsic safety and economic benefits to mine operators." The other beneficiary is the community responsible for monitoring the CTBT. For this community, the report states that "wide spread adoption of these [recommended] mining practices will probably decrease seismic visibility and ambiguity."

2

General Comments on the Draft Report of the DOE Working Group

The March 1997 draft report of the DOE Working Group[7] identifies and discusses the major sources that contribute to the generation of seismic signals associated with mining operations. These sources include events from blasting activities and planned and unplanned ground failures. The report provides documentation and discussion that suggest that some of these events may cause concerns for CTBT compliance and verification. As a result, it urges that the mining community be alerted and educated on the visibility of mining-related seismic signals and their ambiguous character.

The DOE Working Group report contains a broad spectrum of useful data and analytical results on the nature of mining-related seismic signals. It is comprehensive in its review of the relevance of the CTBT to the mining industry from a technical perspective. Underground failures that may produce seismic signals are properly categorized in the report as (1) planned failures, which include controlled failures (e.g., planned pillar blasting and the initiation of block caving) and uncontrolled failures (e.g., strata caving in mining operations), and (2) unplanned failures, which include events such as pillar collapses, coal bumps, and rock bursts. The techniques presented in the DOE Working Group report for recording and analyzing seismic signals can be a valuable tool for assessing blasting performance in mines.

Some of the signatures (e.g., seismic wave forms) of mining-related seismic signals can be similar to those of a nuclear test. Current instrumentation and the methods used to process and analyze seismic signals are not always capable of discriminating between a chemical and a nuclear blast. The recommendations of the DOE Working Group's report focus on modifications to blasting and underground mining practices that will reduce the amounts of energy placed in the ground (i.e.,

[7] The executive summary of the March 1997 draft report of the DOE Working Group is included as Appendix B.

explosive charges used in rock blasting and energy from bursts or collapses) in an effort to reduce regional amplitudes of seismic signals. The DOE Working Group's recommendations place the burden on the mining industry to reduce the amount of energy going into seismic signals at the source rather than on the monitoring community to identify technical means for discriminating signals. An alternative approach, mentioned more briefly in their report, is to reduce the ambiguity of the nature of mining-related seismic signals.

The recommendations proposed by the working group's report to reduce seismic levels prescribe changes to long-standing mining practices that have been refined to optimize equipment investments and operational costs, efficiency, and safety. The committee believes that the adoption of many of the working group's recommendations could result in a substantial increase in operational mining costs. Unfortunately, the DOE Working Group report makes no attempt to address these cost factors, without which the industry will not be readily receptive to the recommendations. The quantification of these costs is at best a difficult task and is best accomplished on a mine site-specific basis. Some generalized cost calculations associated with adopting some of the blasting recommendations are given in Table 1 and further discussed in Appendix A. In this example, drilling costs associated with changes in blasting practice may increase by a factor of two.

Most of the blasting recommendations made in the DOE Working Group report are based on textbook blasting practices and are dated. Rock breakage is a costly unit operation that is given a high degree of technical attention at most

TABLE 1 Calculation of the cost associated with reducing blasthole diameters and bench heights for two hypothetical cases.

Design Factor	Example 1	Example 2 (modified Example 1)
Bench height	50 ft.	25 ft.
Blasthole diameter (design)	10 in.	8-in.
Hole spacing pattern	24 ft.	17 ft.
Stem length	20 ft.	13 ft.
Yardage of blast	1967 yd^3	267 yd^3
Explosive loading (1 lb/yd^3 per blasthole	1022 lb.	262 lb.
Number of blastholes to meet a weekly production rate of 300,000 yd^3	281	1124
Drilled length per week	14,050	28,100
Weekly drilling cost (at $2 per foot)	$28,000	$56,200
Annual drilling cost[a]	$1,461,200	$2,922,400

NOTE: Example 1 summarizes a typical blast design, whereas Example 2 is the modified blast design that limits the charge size used in Example 1 in response to recommendations by the DOE Working Group. This calculation is further discussed in Appendix A.

[a] Costs depicted are a result of calculations for the hypothetical examples; actual drilling costs could vary by 25% or more.

large mines. Some of the methodologies described in the working group's report have been used at many mines to monitor ground vibrations adjacent to structures, maximize blast design and efficiency, and minimize damage to open-pit walls. However, in the case of the DOE Working Group report's recommendation on slice mining, the technique is not a commonly known mining engineering method, is unreferenced, and is inadequately documented in the report. Parts of the working group's report are written in such a way as to imply that the mining industry has a limited understanding of the scientific, technical, environmental, and economic benefits of various blasting practices. The DOE Working Group report as written implies that "we are here to help you," and that controls and assistance from outside the industry are needed to ensure that blasting is done appropriately.

Despite the above criticisms, the DOE Working Group report could be highly useful if reframed as a resource document to inform the mining industry on the relevance of the CTBT to the industry, in terms of mining blasts and ground failures, and possible solutions to blasting problems pertinent to visible mine blasts. The report also identifies the need to consider similarities and differences of U.S. mining practices with those used internationally.

3

Restatement of the Problem

The DOE Working Group draft report examined the nature of seismic signals related to domestic mining activities. The report then indicated that it was desirable to reduce the visibility and ambiguity of these seismic signals. Although measures to reduce both were mentioned, the recommendations clearly stressed reducing the level of visibility. The proposed solutions indeed would reduce the amount of energy placed in the ground. The difficulty is that the recommendations encourage changing mining practices without an examination or recognition of the economic consequences to the industry. Whereas the quantification of these costs is difficult and best performed on a case-by-case basis, most mines operate in a highly cost-competitive environment and over time have optimized their practices. The NRC committee believes that major departures from current operating practices in light of the working group's recommendations can likely have adverse economic consequences.

The NRC committee, therefore, favors an approach that reduces ambiguity, or uncertainty, of seismic sources. This may be a more practical solution than one that seeks primarily to reduce visibility, although reducing visibility may be the preferred solution in some limited instances. Moreover, as suggested in the next chapter, reducing the ambiguity of seismic signals would be less intrusive to the U.S. mining industry and is more likely to secure the voluntary cooperation of mine operators in promoting the confidence-building objectives of the CTBT.

With the availability of accurate, mine-specific information, seismic signals that create ambiguity probably will occur only infrequently. Because of their irregular and unplanned nature, seismic signals produced by rock bursts and coal bumps will tend to be more ambiguous than those resulting from blasting operations.

Figure 4 is a graphical depiction of the likely seismic visibility of domestic mines demonstrating roughly the proportion of operating mines that may be visible to the CTBT monitoring network. A large majority of mines would be invisible. Among those visible mines, most could be calibrated through a voluntary exchange

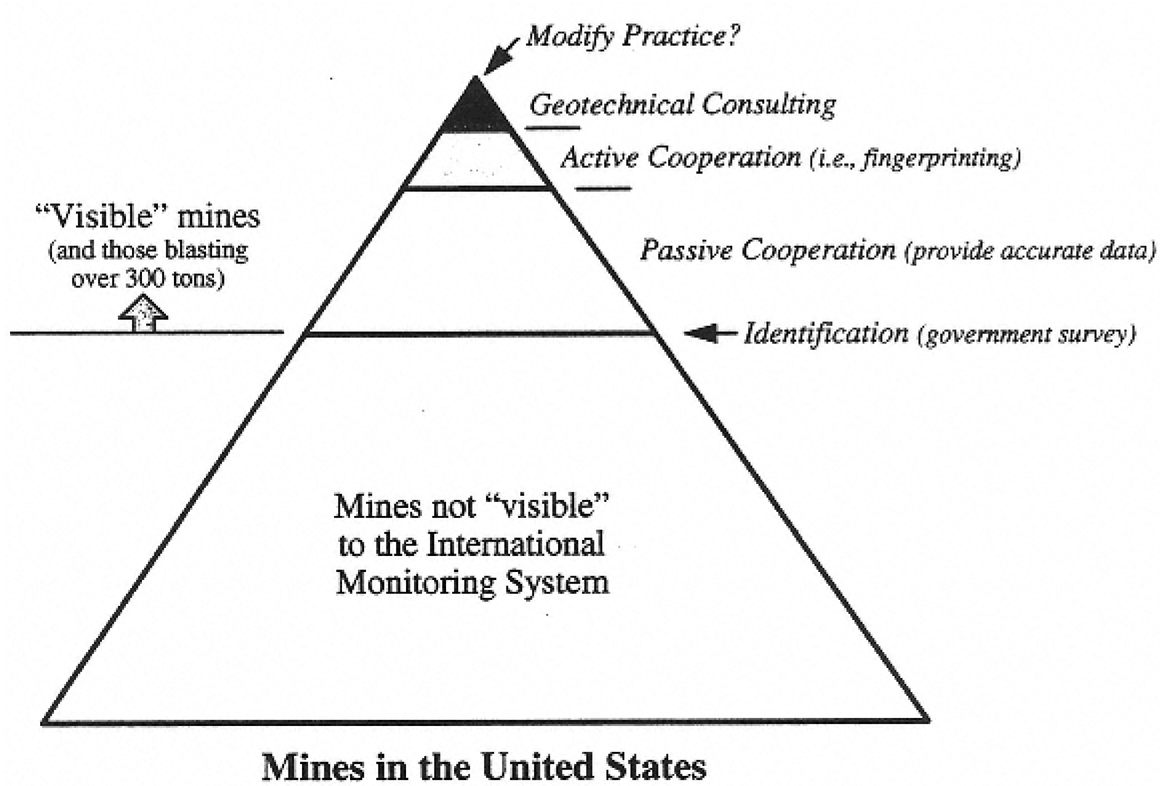

Figure 4 Conceptual distribution of U.S. mines in terms of their seismic visibility under the CTBT monitoring regime. The percent of "visible" mines probably is exaggerated. On the right are a series of cooperative steps that could be undertaken at "visible" mines, starting with their identification for purposes of complying with the confidence-building measures provisions of the treaty. Passive cooperation would involve active mines providing accurate data on their largest blasts and collapses, as proposed in Chapter 4 of this report. Active cooperation would include the on-site monitoring ("fingerprinting") activities that are proposed in the DOE Working Group report, and could include the fielding of calibration explosions. Before making a decision to modify mining or blasting practices, a company could choose to consult with seismic, blasting, or underground engineering experts to identify ways to eliminate its anomalous signals. In all cases, the program should be voluntary.

of information (see Chapter 4) between the mining industry and the U.S. agency responsible for CTBT monitoring. An example would be the one-time provision of data from a few large blasts. Most of the remaining mines producing potentially ambiguous, visible events could be "fingerprinted" through a relatively unobtrusive program of active cooperation such as that proposed in the DOE Working Group report (see text box), whereby multimedia, on-site monitoring of blasts by a designated agency would be performed. Only a small fraction of mines—perhaps none—would need to consider the modification of mining practice as a viable alternative. Of course, the mine operator would consider the cost of lost production and the inconvenience of a possible on-site inspection in the context of other measures to resolve the problem.

SAMPLE CALIBRATION SYSTEM FOR ON-SITE BLAST MONITORING

"The main design goals for the calibration system are that it must be deployable by one or two people in approximately one to two hours at a remote site. The minimum source information it must provide is the shot time and location of the event. Since a supplemental goal of the system is a quantification of the character of the source, in the case of surface explosions, information associated with the design and detonation of the explosions is useful. Video and acoustic measurements that supplement the primary seismometers are included for this purpose. The system should be able to run unattended for hours to days depending on the particular application. The requirement for unattended operation is to accommodate safety issues in the mine at the time of detonation. The ability to record data over a period of days (excluding video) provides the opportunity to use the system to monitor activity in a mine or mining district for an extended period of time with little or no intrusion on the commercial activities."

"The total cost of [a] portable system [described in the DOE Working Group report] is approximately $25,000…Thus, a moderate-cost portable system is available that can be used to obtain ground truth information from a number of different sources in widely separated geographical locations with a minimum of impact on the mine."

Extracted from March 1997 DOE Working Group draft report, *Ambiguity and Visibility of Seismic Signals from Mining Activities: Benefits to the Mining Industries and to the Communities Monitoring the Comprehensive Test Ban Treaty (CTBT),* pp. 4-25-4-27.

A strength of the DOE Working Group report is in identifying and documenting the potential impact that blasting in the mining industry may have on compliance monitoring for the CTBT. The possibility that commercial mine blasting could cause difficulty in CTBT compliance is unfamiliar to most mining executives. Thus, the report might be revised primarily to describe and document this problem. In this form, it would be a valuable resource document to aid in gaining support for a voluntary cooperative program (see Chapter 4) for reducing the ambiguity of mining-related seismic signals.

4

An Alternative Approach

BACKGROUND

As mentioned in Chapter 1, the CTBT treaty language contains voluntary confidence-building measures. If any blast is detonated as an explosion (a single delay) of more that 300 metric tons of explosives anywhere in a nation's territory, the treaty suggests that the nation should provide information about each blast to the Comprehensive Test Ban Treaty Organization (CTBTO) in Vienna. Such large single blasts are quite rare. The information should provide, possibly in advance, "details on location, time, quantity and type of explosives used, as well as on the configuration and intended purpose of the blast." In addition, the treaty asks that each state party, after the entry into force of the treaty, provide to the CTBTO's Technical Secretariat on a voluntary basis as soon as possible information related to those other chemical explosions (e.g., ripple- or delayed-fired blasts) that total greater than 300 metric tons. The information would include "(a) the geographic locations of sites where the explosions originate, (b) the nature of activities producing them and the general profile and frequency of such explosions, and (c) any other relevant detail, if available."

COOPERATIVE MEASURES

Passive Cooperation

Prominent among the "relevant detail" in the previous paragraph could be a *voluntary,* one-time reporting in the first year after entry into force of the CTBT of the times and locations for three of the largest blasts from mines blasting over 300 metric tons of explosives. Additional information on charge per delay and delay intervals would also be useful. In subsequent years, additional requests for routine blasting information from a mine would be rare. If these one-time data were available from most mines that emit detectable seismic signals, it would be possible for monitoring agencies to construct a grid of travel-time models and corrections that would enable very accurate locations for all events at or near those mines.

Such data would also make it possible to acquire and keep updated a library of characteristic events from each mine so that a good record at even a single seismic station could be used to identify precisely from which mine, by name, the signal came. This ability would greatly reduce the ambiguity of many small signals detected by the CTBTO seismic monitoring system and would make it possible to rapidly obtain confidence-building information from the mine to explain any questionable signals.

The determination of blast origin times and location would, ideally, be accurate to the nearest 0.1 second and 100 meters. Larger errors (e.g., minutes) in the origin time, would not be a serious problem; however, accuracy of one second or better is desirable. The required time accuracy could be obtained by manually depressing a firing switch simultaneously with an accurate radio or satellite time mark and allowing for an experimentally determined firing delay. Another, possibly more accurate method of time estimation could be using a signal from a near-source seismometer equipped with a global positioning satellite (GPS) time-code receiver. The location accuracy of the initial explosion, and possibly of the centroid of the explosions, could be determined by reference to a topographic map or by use of a hand-held GPS receiver.

Some mine operations, particularly those with a history of rock failures, may choose to participate in the data gathering even if their explosions fall below the 300 metric ton threshold. Data from these mines could be useful if there were local seismographic networks near the mines (e.g., such as in California) or if the shots were particularly well-coupled or concentrated in time (e.g., large charges per delay and/or short delay intervals).

Information on significant collapses or other rock failures in mines that might be observed seismically was not suggested as one of the voluntary measures in the treaty. However, it would be extremely useful from a monitoring point of view if mine operators would report the location and approximate time of up to three—if any—of their largest collapses or rock bursts that occurred just before or within a few years after entry into force of the CTBT.

Active Cooperation

Those very few mining operations, as discussed in Chapter 3, that might emit large, ambiguous signals that might cause consultation and clarification inquiries from other nations may want to advance to active measures, such as the installation of an unintrusive, on-site monitoring system of the type discussed in the DOE Working Group report (see text box in Chapter 3). Some of these data may be transmitted to the inquiring countries and to the CTBTO via the appropriate U.S. agencies. Such efforts would be in addition to the passive data gathering efforts outlined in the previous section.

HOW COOPERATION COULD WORK

A technical agency (or agencies) of the federal government (e.g., the Mine Safety and Health Administration and/or the U.S. Geological Survey)[8] would be responsible for collecting mine blast and event data and providing them to a policy-oriented agency of the government (e.g., the "U.S. CTBT National Authority," yet to be established). The policy agency would be responsible for reviewing the data and sending the appropriate information to the CTBTO's Technical Secretariat.

The designated U.S. technical agency would be responsible for determining which mines should be asked to participate and would receive and collate the data from the mines. The data would then be evaluated in comparison with seismological records of events, with the goal of identifying those mines whose seismic signals are visible to the International Monitoring System (IMS). Those mining operators would be asked if they would volunteer additional calibration data that could be used in the case of a request for consultation and clarification under the treaty. The results of this data gathering and analysis would be forwarded to the policy agency for possible transmittal to the CTBT Organization, in compliance with treaty confidence-building measures.

Operators for those few mines that generate seismic signals large enough to be located by the IMS and appear on the bulletins distributed to all parties to the treaty may choose to deploy an on-site, active monitoring system such as that proposed by the DOE Working Group. The data and results of the on-site fingerprinting exercise would also be provided to the policy agency, which could transmit the relevant information to the CTBTO, if appropriate.

In the year of the treaty's entry into force (EIF), or earlier, the U.S. technical agency would survey the mining industry with respect to its use of explosions over 300 metric tons. Subsequent annual surveys would be used to identify new mines blasting over that threshold (and mines no longer conducting large blasts), as well as mines having had significant collapse events. Prior to EIF, professional and industry associations should begin educating their members on the possible impact of the CTBT on the industry, the importance of communication and collaboration that will be needed from some mines, and the types and accuracy of the information that is desired.

[8] Of existing federal agencies, the Mine Safety and Health Administration (MSHA) and the U.S. Geological Survey (USGS) are cited here because of their existing responsibilities related to the U.S. minerals industry. The MSHA has responsibilities with respect to the oversight and regulation of all U.S. mines, including collecting information on blasting and mining collapses. MSHA already surveys all U.S. mines on a quarterly basis. The USGS, which is a scientific and technical agency with no regulatory or land management responsibilities, monitors all seismic events in the country, including mine blasts, and currently has an agreement with the Department of Defense to provide CTBT-related data on U.S. mine blasts and events. The USGS also surveys mines annually, and its most recent survey included requests for information on blasts over 300 metric tons; there is no equivalent international survey.

An additional role of the technical agency would be to gather, for any calibration shots, the arrival time and seismograms from all available seismometers, including those not in the IMS, and make those data available to the policy agency for possible transmittal to the CTBTO.

ADDITIONAL BENEFITS

In addition to the monitoring benefits, those countries that participate in the voluntary calibration efforts will be better able to respond to questions of consultation and clarification; only the mining operation that emitted the signal of concern need be contacted. Without calibration, the location error ellipse for a particular seismic event may contain many mines, all of which would likely have to be contacted. Calibration of travel-time models will also result in a substantial increase in the understanding of crustal structure and velocity, and improvement in earthquake locations in areas where local networks do not exist.

5

Communications

The information contained in the report authored by the DOE Working Group (with appropriate revisions) and in this review should be disseminated to the relevant communities. The primary audience should be the mining industry, largely represented through their principal trade associations and professional societies. The seismic monitoring community and those involved in CTBT policy issues are also important communities for which the information would be beneficial.

For these relevant communities, the information dissemination should include, at a minimum, presentations and panel discussions at national, regional, and state-level meetings. Annual meetings of the mining-related trade associations and professional societies typically involve attendance by management and supervisors who are responsible for corporate-level decisions. State-level or regional meetings may, in addition, include project engineers, scientists, and others who are directly involved in carrying out mining practices. By addressing the interested parties directly, a high degree of interaction can be achieved to (1) disseminate information, (2) obtain feedback from professionals in the industry, and (3) assess the qualitative impacts of the recommendations.

For those groups that would not necessarily be directly affected by the recommendations but which may have peripheral interests in the materials, dissemination should include announcements in journals and newsletters, and on the Internet of the availability of the information.

Although these audiences are interrelated professionally and commercially, they are diverse. For that reason, no single organization can be relied upon to disseminate the objectives of the CTBT monitoring system and the means by which the U.S. mining community can easily and usefully cooperate in the implementation of the treaty and building confidence in the verification regime.

TRADE ASSOCIATIONS

Industry participation in the activities of national or state trade associations is purely voluntary. Currently, the National Mining Association (NMA) is the principal trade association for the domestic mining industry. The NMA resulted from a merger in 1995 of the American Mining Congress and the National Coal Association, which formerly represented the hard rock and coal industries, respectively. The NMA currently has a membership of most of the major mining companies that utilize explosives in the production of ores and coal. Another segment of the industry is represented by the National Stone Association (NSA), which is the trade association representing about 70 percent of the crushed stone, sand, and gravel mining industry. The use of explosives is integral to their operations.

The Institute of Makers of Explosives (IME) is a trade association dedicated to promoting the safe use of explosives for industrial and research applications. Membership within the IME comprises many of the manufacturers of commercial explosives and initiating devices used in the mining and quarrying industries and chiefly involves corporate managers who are involved in policy decisions on the federal and state levels. NMA, NSA, and IME are based in Washington D.C. for the primary purpose of representing the interests of member companies and closely following policy issues that may affect their members.

All three trade associations should be informed of the CTBT objectives in the direct manner discussed above. Of the three associations, the NMA may be the broadest single avenue for explaining the objectives of the CTBT and the means by which the domestic mining industry could be affected by the treaty. Through a variety of meetings and annual events, information about the treaty can be presented to different groups representing senior management, operating personnel, engineers, and vendors. These meetings should include the two objectives that have guided the NRC committee in preparing this review. First, voluntary and cooperative measures probably could be implemented without creating an additional burden on the industry (see Chapter 4 of this report). Second, active participatory measures contemplated in a few instances are designed to foreclose any possibility of an on-site inspection. The NRC committee believes that cooperation from the domestic mining industry should be forthcoming and widespread.

PROFESSIONAL SOCIETIES

A number of professional societies with affiliation to the mining industry exist. The largest is the Society for Mining, Metallurgy and Exploration (SME), which is part of the American Institute of Mining, Metallurgical and Petroleum Engineers (AIME). SME represents a wide range of professional engineers (principally mining engineers) and scientists (e.g., geologists, geophysicists, mineral economists, hydrologists) whose work is related to the extractive industries. These industries include energy and base metal resources extracted both from open pit (surface) and underground mines. Professionals include upper-level managers, supervisors, project and planning engineers, consultants, academicians, etc.

SME conducts one national meeting each year with attendance of approximately 5,000 from the United States and throughout the world. Specialty presentations (short courses, mini-conferences, etc.) are hosted prior to the meeting. A presentation of the CTBT-related information and materials could possibly be made during this time, in addition to a presentation during a regular session during the main meeting.

In addition to the annual meeting, there are a number of regional SME chapters, largely in states with active mining, that usually conduct monthly or quarterly meetings. Both the national and state forums provide an excellent opportunity to inform a broad spectrum of mine operators about CTBT issues.

The International Society of Explosives Engineers (ISEE) is a professional society whose membership represents explosives engineers, explosives manufacturers, drilling and blasting supervisors, hands-on blasters, academicians, consultants, and researchers. The annual meeting, as well as more frequent meetings of ISEE state and regional chapters, provide an excellent opportunity for dialogue with blasting practitioners about CTBT monitoring issues.

The availability of the NRC and DOE reports and other information on mining activities and the CTBT should be announced through the Internet and newsletters to other professional societies, some of the members of which will have an interest (e.g., Seismological Society of America, American Geophysical Union, Geological Society of America, Society of Exploration Geophysicists, Association of American State Geologists).

GOVERNMENT AGENCIES

Agencies of the federal government with responsibilities related to CTBT implementation, monitoring, verification, and research are the Departments of State, Defense, and Energy, as well as the Central Intelligence Agency and the U.S. Arms Control and Disarmament Agency. Other agencies with responsibilities related to seismic event characterization, mine regulation, and minerals information are the U.S. Geological Survey (USGS, Department of the Interior), the Mine Safety and Health Administration (MSHA, Department of Labor), the National Institute of Occupational Safety and Health (NIOSH, Department of Health and Human Services), and the Energy Information Administration (EIA, Department of Energy). Except for MSHA, NIOSH, and EIA, interested parties within these agencies can be reached through the CTBT “Backstopping” Committee and the CTBT Verification and Monitoring Task Force (both in the U.S. Arms Control and Disarmament Agency), and through the Interagency Working Group of the National Security Council. For MSHA, NIOSH, and EIA, targeted efforts need to be made to identify appropriate contacts for outreach efforts.

There may be considerable benefit from communicating these data, ideas, and proposals internationally. Those government agencies with representatives to the international CTBT Organization (CTBTO) should be encouraged to distribute this information to the CTBTO.

6

Additional Research

Additional research could further contribute to reducing the visibility and ambiguity of seismic signals resulting from mining activities. Specific research needs include issues of sympathetic detonations during mine blast initiation, the development and application of precise electronic detonators and instrumentation, and continued work in the areas of ground failures and seismic discrimination. Research is also needed in discrimination of seismic signals from mine blasts and ground failures from other seismic events.

SYMPATHETIC DETONATIONS

Sympathetic detonation of explosives is the unintended detonation of an explosive charge by the detonation of another explosive charge in the proximity. Sympathetic detonations can produce undesirable fragmentation, undesirable vibration, backbreak, and flyrock resulting in adverse cost and safety impacts. Many of the causes for sympathetic detonations that occur during blasting are not well understood. Under ideal conditions, with unconfined explosive charges, standard tests such as the flash-over and gap tests have been developed to document the stand-off distances between two explosive charges of specific diameters and sensitivities. Under these conditions, it is generally the shock pressure from the donor charge that initiates the acceptor charge. However, the occurrence of sympathetic detonations between loaded blastholes has been documented in the field. In such instances, the sudden burst of shock pressure and heat can emanate from a detonating hole through openings along joints and bedding planes. These pressures can be of the level required to initiate a detonator and may, in some cases, initiate the priming high explosive.

Sympathetic detonations can also occur in coal mine blasting when heat and open flames of initiating explosives react with coal dust or methane gas pockets.

In addition, there are documented occurrences in which the heat from the oxidation of pyrite in the vicinity of the main explosive charge of ANFO (ammonium nitrate-fuel oil mixtures) within the borehole has prematurely detonated holes within a shot.

The case presented in the DOE Working Group report, in which 40,000 lb. of explosives simultaneously detonated at a large western surface coal mine, has illustrated this issue. Sympathetic detonations of such large quantities of explosives are rare; those related directly to the quality and reliability of explosive products or devices are even rarer. However, external geological and environmental conditions that may contribute to sympathetic detonations are of interest for future study.

PROGRAMMABLE DETONATORS

Research in the area of programmable detonator use as a means of improving the precision of explosive initiation times may be of interest. In reality, however, the improvement of timing accuracies they promise may only marginally improve errors inherent to existing electric and nonelectric detonators. These errors in timing of explosive initiation are currently only a few percent of the design delay times. Resulting marginal improvements may not be detectable at far-field distances.

Nonetheless, the degree of improvement does need to be quantified. Several U.S. companies are developing programmable detonators. They are a few years away from marketing these devices. More field-scale and production tests are necessary to verify the accuracy of the devices. Research in this area may be limited to providing access to mine sites for detonator manufacturers in order to conduct production testing. This is an area of research in which the mining industry should take the lead and coordinate with the explosive manufacturers.

GROUND FAILURES

Further research is needed to understand and control the mechanisms associated with planned and unplanned failures. The following two approaches should be considered: (1) controlled tests conducted in the field and analysis of these results using geomechanical principles and models, and (2) an expansion of efforts to record, predict, and analyze unplanned ground failures. These efforts would be beneficial for developing seismic fingerprints of these events, particularly unplanned failures such as bumps and rock bursts. In addition, such research could provide important information for improving mine design and for developing warning systems prior to the occurrence of these failures.

INSTRUMENTATION AND ANALYSIS OF GROUND MOTION WAVEFORM CHARACTERISTICS

One area of research that could greatly benefit the mining industry is the development of affordable monitoring equipment with a higher resolution level than is currently available. Another is the provision of a more sophisticated means (i.e., through software development) of analyzing the spectral content of ground motion wave forms consistent with the methods used in seismology. Through such effort, a common analytical approach to wave form analysis among seismologists and mining engineers should be sought.

DISCRIMINATION OF SEISMIC SIGNALS

The availability of source information from mining blasts in the United States would allow for the improvement of travel-time models and earthquake location algorithms. One goal of further work in this area would be the development of regional velocity models that could be used to greatly improve seismic event locations. Improved earthquake locations could benefit earthquake characterizations, and in some cases, damage assessments and emergency response.

7

Conclusions

Based on its review of the draft report of the DOE Working Group, the NRC committee concluded the following:

- Most U.S. mines will be not be "visible" to the CTBT monitoring system.
- Most large U.S. mines have optimized their operations in order to remain competitive and could be adversely affected economically by the suggested changes in blasting practices or re-engineering of mine designs proposed in the DOE Working Group report.
- The CTBT monitoring system would benefit greatly from the voluntary participation of "visible" mines in a few, simple, cooperative measures that would have little or no impact on mining operations and could, in some cases, improve blasting efficiency or mine safety.
- A stepwise approach (drawing from the DOE Working Group report), beginning with simple communications between mine operators and government seismologists, would be adequate to address most of the problems of event ambiguity in CTBT monitoring. If not, then it may be necessary to employ active mine monitoring techniques for those mine operations that produce problematic seismic signals.
- A voluntary approach that results in decreasing the visibility or ambiguity of seismic signals originating from mining operations would also benefit the United States by setting a positive example for other countries to participate in confidence-building measures under the treaty regime.
- It is likely that an effective voluntary program would be acceptable to the mining industry, and could therefore be fully implemented soon after the entry into force of the CTBT.

Appendix A

Specific Comments on the Draft Report of the DOE Working Group

Chapter 2 of this review presents general comments on the March 1997 draft DOE Working Group report, *Reducing the Ambiguity and Visibility of Seismic Signals from Mining Activities.* The NRC committee authoring this review also presents specific comments on many of the technical aspects of the DOE report within this appendix. The intent is to provide these comments for consideration by the DOE Working Group in any revision to their report. These specific comments have been placed in an appendix to avoid distracting readers from the principal focus of the NRC study, that is, voluntary efforts that could reduce the ambiguity associated with seismic signals originating from mining activities.

BLASTING

Problem Statement

The DOE Working Group identified important issues for the mining industry with respect to the possible impact of the CTBT, as well as specific problems relating to the visibility and ambiguity of mining blasts. However, statements relating to the magnitude and extent of these problems are undocumented and may be misleading. For example, the report asserts that one in 20 shots contains sympathetic detonations, represents misuse of explosives, or noncompliance with safety regulations. This assertion implies that, of the estimated 150,000 to 200,000 blasts that are conducted annually in the U.S. mining industry, 7,500 to 10,000 represent blasts in which mishaps occur and may produce anomalous signals. The NRC committee is not aware of data that could justify this assertion and none are presented in the DOE report. Although it is generally recognized that many blasts do not perform exactly as designed, such incidents usually do not detract significantly from the overall performance of the blasts.

Representativeness of the Study Site

The principal site of the research effort that forms the basis for defining the blasting issues of concern and for developing the report's recommendations comprises a single coal mining operation (Black Thunder, Wyoming). The site, a large coal mine with casting operations, may not be representative of most large blasting operations in the United States. Because of the narrow scope of the investigation, it is risky to extrapolate the scientific information acquired for one mining operation that may be representative only of blasting operations of that type (casting). Hence, the conclusions and recommendations lack the foundation that is needed if they are to be applied to operations throughout the United States.

The draft report clearly points out that there is no difference in the signals from single chemical explosions and from nuclear explosions when energy is normalized to TNT equivalents and the same source geology is involved. Other aspects of the source such as coupling (defined as the efficiency of the transfer of explosive energy into seismic waves) further affects the amplitude and hence, visibility. This information, as well as resulting complexities in the seismic wave forms, has been recognized for many years by explosives engineers and mining engineers working in the vibration fields.

With respect to the research leading to the conclusion that there is a difference between casting and fragmentation shots, the report does not distinguish between the two types of blasting with recommendations specific to each practice. The coal shots used to exemplify fragmentation shots do not necessarily represent fragmentation shots in hard rock mining (i.e., mining in which the mineralized ore deposit is blasted prior to comminution). The latter have very specific fragmentation requirements that are met using carefully placed time delays. Because the source geology and delay sequence used in these shots differ from those of coal mine blasting, the wave form frequencies also show quite different characteristics. Hence, the data forming the basis for recommendations that apply broadly to the mining industry as a whole have not included the subset of hard rock mining.

Blasting Recommendations

Recommendations are discussed in Chapter 4 of the DOE Working Group report. Links between the research findings and the recommendations often are insufficiently established. One notable recommendation concerned the “slice mining” method, which was not referenced or explained in the report and is largely an untested method. Based on an oral explanation of the slice mining method to the NRC committee by members of the DOE Working Group, the committee found the method may create a highwall safety exposure risk, require operating under unsafe and congested conditions, and may not lend itself to the use of large-scale mining equipment. Each of the other blasting-related recommendations are considered below.

Reduction of Charge Weights

The recommendation about charge weight reduction can be implemented in a number of ways summarized in the DOE Working Group report. This includes reduction of borehole size, reduction of blasting bench height, the use of decked and decoupled charges within the hole, more stemming (implying shorter charge lengths), and less subgrade drilling. Unfortunately, the DOE Working Group report does not consider the economic impacts of these recommendations. The NRC committee believes that the economic impacts may be substantial because of the costs for additional drilling.

Amount of Explosive per Delay

The assertion that a “20 to 50 percent reduction of the explosive would be required before measurable reductions in vibration levels can be realized” (draft report's executive summary, see Appendix B, p. 49) is not substantiated and no references are cited. The report does not adequately discuss the feasibility of reducing the amount of explosive per delay while achieving fragmentation and haulage objectives, as well as overall financial goals. The NRC committee agrees that reducing the quantity of explosives detonated on one time delay will reduce ground motion amplitudes. However, the specific correlation between decreased explosives and the reduction of the seismic amplitudes is unresolved.

Smaller Borehole Diameters and Smaller Bench Heights

Employing shorter blastholes of smaller diameters generally increases the drilling costs. The economic impact of this can be assessed for a hypothetical example.

In considering production blast design modifications (versus wall control blasts), the powder factor must remain constant, as it is set for a particular geology, fragmentation size, and ore displacement requirement. Given a typical bench height of 50 feet and a blasthole diameter of 10 inches (blasthole diameters are determined by the designed bench heights), to achieve a 50 percent reduction in explosive weight, a reduction in hole diameter and length or bench height is necessary. For operating convenience, it would be most appropriate to break the 50 feet bench into two 25 feet benches. Reducing the bench height to 25 feet would reduce the blasthole diameter to 8 inches. This would result in a reduction of the explosive loading density from 34.1 to 21.8 lb/ft. (assuming an average explosive density of 1 g/cm^3 for mixtures of ammonium nitrate/fuel oil and emulsion-based products).

As an illustrative example, the impact of this change on the costs of drilling can be roughly assessed (see Table 1, Chapter 2 of this report). The examples given are acceptable for good blast design and meet most production purposes. The explosive loading per hole is reduced by the greater than the 50 percent recommended by the DOE Working Group report.

The doubling of annual drill footages almost certainly would require the acquisition of an additional drill rig (acquisition cost on the order of $2 million). The increase in blasting costs, although not as severe as the increase in drilling costs, also can be assessed. The cost of the explosives would remain the same for a constant powder factor. However, quadrupling the number of holes requires four times the number of boosters and detonators, as well as labor time of the blasting crew. Since these costs typically represent about 2.5 percent of the total blasting costs, an increase of about 10 percent in boosters and detonators would further add to the extra costs resulting from decreasing the charge per blasthole, as given in the hypothetical example.

Decoupled and Decked Charges

The working group's report claimed that sizable reductions in the explosive weight per delay can be achieved by decoupling the explosive charge from the borehole wall. The use of decoupled charges usually is not acceptable to most mining practices, as it represents a possible waste of explosive energy and dollars spent. However, for wall control, decoupled charges have been used for over 30 years by the mining industry to minimize damage to intermediate and final open pit walls in order to improve wall stability. In recent years, dozer ripping/trimming has been practiced to develop certain ultimate slope walls to eliminate blast damage altogether. It is well recognized that good blasting practices must achieve a balance between maximizing fragmentation and minimizing wall damage.

The decking of charges, however, does represent a valid modification that will reduce the charge per delay that mines may be able to live with, but only to the extent that the stratigraphy within the borehole allows.

More Stemming and Less Subgrade Drilling

The DOE Working Group report also recommended increasing the stemming and using less subgrade drilling as a way to decrease seismic visibility. These modifications usually are not acceptable, as these regions of the borehole (the top near the collar and the base below the pit floor) are critical in blast design. If the boreholes are not properly loaded with explosives, operating efficiency may be directly affected. Using less explosives at the hole collar produces oversized fragments that may be difficult to remove by excavation equipment. Less subdrilling in hard rock mines will produce irregular pit floors that are not cut to grade and on which equipment may be difficult to operate.

Delay Period

Specific delay periods are not recommended in the DOE Working Group report. However, delay periods of up to and over 100 milliseconds is noted as being desirable to increase the probability of mine blast discrimination and to lower seismic amplitudes. Although scientifically sound, this recommendation is made without considering the accompanying impact on mine operations. The 100 millisecond interval is, unfortunately, one of the worst intervals for near-mine site ground motion disturbance in most geologies. Such intervals generate frequencies near the natural frequencies of structures (near 10 Hz) and promote shaking to nearby residential dwellings. Moreover, blasts designed to achieve fine fragmentation must use small delay intervals on the order of 9 to 25 milliseconds. High delay intervals are not effective in such fragmentation design (versus casting) practices.

The DOE Working Group report recommends signature-hole tests to establish optimum delay intervals, in order to shift near-field frequencies away from the natural frequencies of structures. However, these tests may not be as reliable as suggested. Variations in geology and explosive detonation properties from test to test yield varying results. The results of signature tests, when applied to full-scale production blasting, may not alleviate ambiguity.

Use of Programmable Detonators

The DOE Working Group stated that “precise, programmable electronic detonators hold considerable promise in the control of blast induced ground vibrations by eliminating the inherent scatter in the detonator firing times and providing unlimited choice of delay intervals.” However, programmable detonators are not widely available at this time and their projected costs (3 to 10 times the costs of currently available electric and nonelectric detonators) cannot be justified based only on the reliabilities measured under ideal (non-field) conditions. There is limited testing being conducted in operating situations and manufacturers are reluctant to specify both projected sale prices, as well as statistics for actual initiation timing for production situations. Therefore, the recommendation for wide-spread use of programmable detonators is unrealistic at this time.

Current delay times for initiation systems are considered reliable, cost-effective, and within the acceptable ranges required by the mining industry. Most nonelectric detonation systems have a standard deviation from ±2 to 8 percent and have proven to be reliable, depending on the range of delay times—from a few tens of milliseconds to a few hundreds of milliseconds. The variation in actual detonation time is a function of lot number, storage conditions, and other factors and is usually taken into account by the blaster when designing blasts. It is uncertain that improvements to current detonator accuracies will be detected regionally in seismic signals. On the positive side, improvements in fragmentation and muckpile placement will accompany improvements in accuracy.

Other factors that contribute to variations in initiation timing include explosive performance and the variability of explosive types that may be used within one mine blast. The variability in explosive quality within a blasthole and between blastholes in a shot for a 100 foot blasthole can cause variations in total explosive detonation times on the order of a few milliseconds, and possibly up to 10 milliseconds in the worst case.

Close-in Seismic Warning Stations

The DOE Working Group report suggests that mine operators establish permanent near-site seismograph warning systems at distances of 5, 10, or 15 miles from the mine site to allow a prewarning of signals that could trigger an international monitoring station. (Note that the description in the report of the near-site system given in Section 4.C does not match that of the on-site system recommended in section 4.A.1.3.) Currently, many mines use seismographs that are located 1.0 ± 0.5 mile from the mine site for vibration structure damage control. The NRC committee believes that the industry as a whole currently possesses the expertise and analytical capabilities to assess “desirable and undesirable” blast designs. The recommendation to install distant (more than 5 or 10 miles from the mine) monitoring stations would not likely benefit the mine operators and could be regarded as an excessive and unjustified burden.

The main differences between the seismometers typically used in the mining industry and those used by seismologists is the ability for the latter to detect and measure low amplitude and low frequency responses. The equipment used in the mining industry has 8- to 12-bit resolution and frequency responses that cut off below 1 Hz. As a result, these seismometers do not detect many of the wave phases and long period amplitudes of interest to seismologists. The seismometers are used chiefly to determine if mine blasts generate amplitudes and frequencies that might lead to damage at near-by structures.

If mine seismometers are to serve as a warning system for regional seismic systems, then the two recording systems should have similar sensitivities to detect the necessary wave characteristics of interest to both the mining industry and seismological community. Further, the on-site mine monitoring system that is proposed is relatively expensive and requires expertise that is not routinely available at the mine. A more effective means to obtain accurate blast times and locations may be the use of GPS (global positioning satellite) techniques.

GROUND FAILURES

Underground failures that may produce large seismic signals are categorized in the DOE Working Group report as planned and unplanned failures. Planned failures include (1) controlled failures (e.g., planned pillar blasting and initiation of a block cave) and (2) uncontrolled failures (e.g., strata caving). Unplanned failures include catastrophic events such as pillar collapses, coal bumps, and rock bursts. Large-scale surface mine and waste dump failures that could generate distinguishing seismic signatures are not mentioned in the report.

In terms of controlled mine failures, the case studies presented in the report do not indicate any significant visibility issues. The report uses the term “cascading pillar failure” (CPF) to describe unplanned, catastrophic events of pillar collapses. The occurrence of CPF is extensively discussed in the report, although such events cannot be considered as common occurrences. Three possible CPF cases since 1986 are reported in the study, most notably the 1995 collapse at the Solvay mine in Wyoming that resulted in seismic signals of a 5.2 (M_L) magnitude. In typical mining operations in the United States, cascading pillar failures are rare, unlike coal bumps, and improved mine design techniques are likely to further reduce such pillar collapse events.

Pillars usually fail due to secondary extraction in room-and-pillar operations. Also, yield pillars (e.g., in the headgate and tailgate entries of longwall panels) are designed to yield, to accommodate and accept variable stress loading. Such pillar design techniques are now mature, well-proven practices in domestic mining operations.[9]

The DOE Working Group report presents simplistic concepts of mine planning measures to avoid cascading pillar failures (i.e., containment, prevention, and full extraction) that may be applicable only to some coal mine systems. These are basically prescriptive suggestions, but cannot account for individual mine design goals and objectives unless there is thorough consideration of production impacts and financial implications.

A considerable percentage of the coal bump events referenced in the report (Table 3A.1) is from a single mine (Lynch 37) in Kentucky, which is currently closed. Also, it is noted that multiple discrete events are listed for a single day, which is typical of the stress redistribution process. Bump activity[10] and rock burst episodes are probably related to regional tectonic conditions. Contemporary seismic monitoring techniques, including analytical methods for data analysis, are now available that can integrate information from seismic activity at a mine property into a warning system for safety considerations. A prototype of such a warning system for the occurrence of rock bursts is operated at the Lucky Friday mine in Mullen, Idaho, which was installed in cooperation with the former U.S. Bureau of Mines.

CALIBRATION OF MINING SIGNALS

The DOE Working Group report recommends calibration and fingerprinting of active mines, in order to minimize the impact of the CTBT verification system by minimizing false alarms. The working group proposes obtaining this information by deploying portable instruments at "visible" mines to record large blasts.

These recommendations are scientifically valid and practical; the NRC committee amplifies them in its proposed solution in Chapter 4 of this review. Although the

[9] It should be noted, however, that modern mining techniques and operating pressures to achieve high production goals may inevitably lead to larger mining panels or sections (i.e., size increases in longwall panel dimensions). That trend may also increase the seismicity potential (i.e., during caving operations) of reaching "visible" levels in the future. As a result, seismic signals from engineered mine collapses are expected to become more visible in the future as mine production increases and caving operations include stronger more massive rocks.

[10] It may be reasonable to assume that bump severity might increase in the future, as coal mining operations progress to deeper cover depths.

measures themselves would not reduce seismic visibility, they could result in reduced ambiguity by improving identification of blast event locations and providing a fingerprint of mines with large blast events. However, most mines do not maintain the technical expertise or equipment necessary to undertake such a calibration effort and would have to rely on outside expertise to carry this out. The DOE Working Group has not indicated who should perform this task nor to whom the data, once calibrated, should be provided. On the other hand, the NRC committee believes that a more immediate benefit would accrue from the simple collection and reporting of accurate mine blast locations and times utilizing less sophisticated and less costly equipment and techniques than those proposed in the report. These procedures are described in Chapter 4 of this review. They do not replace the on-site calibration and fingerprinting system proposed by the DOE Working Group, but could be used to improve the characterization of mine blasts in a broad, more cost-effective, and timely way.

PRESENTATION OF DATA

Although the DOE Working Group report includes valuable technical information, the presentation could benefit from improved organization and writing. By improving the presentation, useful information could be synthesized in a more logical manner and the significance of data could be appreciated more readily. For example, terminology used to describe details of seismic signals is complex and is discipline-specific to the seismologic community. A high level of knowledge and experience in seismology is needed to comprehend a large portion of the report. If the intent of the working group report is to serve as a reference document for a community that includes the mining industry, the report should clearly convey the issues defining the problem in terms familiar to that industry.

Presentation of data or supporting documentation of several assertions would improve the credibility of the report. For example, in the executive summary of the working group's draft report (see Appendix B) the statement is made that "…the U.S. government and its National Laboratories have engaged in an extensive partnership and joint research with the U.S. mining industry, to identify mining practices that provide intrinsic benefit to mining companies…" A list of companies and types of cooperation and research would be useful, as would be the results of such activities and resulting benefits.

In the draft report's presentation of technical data, equivalent data types are not displayed in the same context and in many cases, graphs and plots of data are missing labels and/or units for axes (e.g., Figure 2.B.7 and 2.B.8). Greater attention to such details would help improve the presentation, particularly for understanding points made in the text and for the evaluation of the data sets. One figure (Figure 2.A.10) has a portion labeled "safe damage zone," whereas in the referenced Office of Surface Mining chart, that portion is labeled the "safe blasting zone."

The level below which seismic signals from mining operations should be of no concern, in terms of visibility, is not adequately defined or discussed. For example, are events only with seismic signals above M_L = 3.0 relevant to CTBT monitoring or might visibility questions arise from events in the M_L = 2.0 to 3.0 range? Seismic magnitudes (M) used in the report need to be defined and labeled consistently. Frequently, it is not clear which of the commonly used earthquake magnitudes are employed.

A goal of the IMS is to have uniform detection capability to some threshold magnitude (3.0 is often mentioned as a goal). This magnitude is a teleseismic measure, m_b (body wave magnitude). Most studies of U.S. mining have made use of regional distance seismic recordings and related these to local magnitude (M_L) or regional magnitude (e.g., m_b, m_bL_g). In the case of earthquakes, m_b and M_L are well correlated in the magnitude range of 3.0–4.5. However, for mining seismicity, this correlation is poor. This is because delayed detonation procedures distribute the P wave over a time window lasting up to several seconds; the shorter period signals (like S_V or R_g) may still be large. The net effect is that local and regional magnitudes may be larger than m_b for most mining explosions.

Appendix B

Executive Summary

Reducing the Ambiguity and Visibility of Seismic
Signals from Mining Activities: Benefits to the Mining
Industries and to the Communities Monitoring the
Comprehensive Test Ban Treaty

March 1997 Draft Report of a
DOE-Working Group

EXECUTIVE SUMMARY

OVERVIEW

Statement of the Problem

The Comprehensive Test Ban Treaty (CTBT), which opened for signature September 24, 1996 and has since been signed by many nations, is intended to preclude any future nuclear testing. After the treaty is in force (following ratification by appropriate countries), the main concern of the international community will be to verify that no nuclear test is performed. Because mining activities world-wide can generate seismic events which might appear as treaty-prohibited explosions, the mining community may be asked to explain visible or ambiguous seismic signals. The mining industry generates seismic signals from surface and underground blasting, and from underground mine failures. Seismic magnitudes of the largest mine collapses have exceeded 5.0 (equivalent to the signal from a 10 kiloton contained nuclear explosion), but more commonly, mine-related events range from magnitude 3.0 to 4.0 (the larger equivalent to the signal from a 1 kiloton contained nuclear explosion).

Ground motions observed at regional distances are highly correlated with mining practices and ground motions in the mine. Mining practices which result in increased productivity, improved safety and minimized in-mine ground motions also produce smaller and unambiguous regional seismic signals. Minimizing unproductive, blasting induced ground motion also makes industry a better neighbor. Thus, the motivation for industry in following these practices is not in the context of the Treaty but in an attempt to maximize their return on investment in mining resources. Further, mines can minimize false alarms under the CTBT by being less seismically visible, i.e. sending out weaker signals, and being less ambiguous, i.e. making sure that the signals have the characteristics of legitimate mining activities.

Verifying international compliance with the Treaty requires the ability to detect and identify small underground nuclear tests. Signals from such an event will have to be discriminated from a background of natural earthquakes, man-made mining and construction activities, and noise from wind and ocean waves. Detection and identification of small seismic events (magnitudes less than 4) remains an area of active research.

Mine blasts are explosions of course, but unlike most underground nuclear tests they are normally composed of many small explosions spread out in both time and space which can lead to modulation in the frequency content of the event that can be used to identify some delay-fired mine shots and distinguish them from concentrated blasts. Earthquakes and single-fired explosions do not exhibit this modulation.

Mine seismic@ from uncontrolled sources (e.g. rockbursts, coal bumps, mine collapses) may have characteristics unlike either earthquakes or explosions. Uncontrolled mine events in the past have been identified by comparing long-period waveforms with computational models. A variation of these waveform matching techniques can be used to identify blasts or mine tremors from a specific mine, to produce a “fingerprint” of the mine. When seismic events are planned to occur at a specific mine, ground truth (specific information obtained at the mine) can be used to determine the event type and characteristics for each of the events.

It has long been recognized that detonation of an explosion in an underground cavity significantly reduces (by a factor of 10 to 100) the amplitude of the seismic signal. It is thought that if a nuclear test were decoupled in some circumstances its signal could be small enough to be masked by another seismic signal, such as a normal mine explosion. Calculations have shown that a single concentrated explosion is detectable within a large delay-fired explosion if the single shot energy is more than about 10% of the total energy of the two explosions.

With this background, the U.S. government and its National Laboratories have engaged in an extensive partnership and joint research with the U.S. mining industry, to identify mining practices that provide intrinsic benefit to mining companies while naturally minimizing the impact of these operations on the monitoring of the Treaty.

CTBT Imdementation

The Treaty will be enforced by an international organization that includes all signatory countries as members. The CTBT Organization (CTBTO) will consist of the Conference of the States parties, the Executive Council, and the Technical Secretariat.

This organization will operate an International Monitoring System (IMS) for treaty compliance using seismological, radionuclide, hydroacoustic, and infrasonic monitoring. Data from the monitoring stations will be transmitted to the International Data Center (IDC) which will process the data and will make results and raw data available to all member countries. Individual member countries may reanalyze the data in any way they wish and may bring questionable events to the attention of the CTBTO.

Before requesting an On-Site Inspection (OSI), States Parties are encouraged to "HZ&~*every effort to clarify and resolve, among themsezves or with or through the Organization, any matter which may cause concern about possible non-compliance with the basic obligations of this Treaty.*" (United Nations General Assembly, A/50/1027) Two voluntary actions are included in the provisions of the Treaty: (1) Consultation and clarification; and (2) Confidence building measures. Consultation and clarification is the process by which countries can ask another for information that might help resolve a questionable event. This process could include the exchange of data or information about a particular source that generated the signals. Confidence building measures are cooperative actions that can be taken by nations to improve the performance of the monitoring system and eliminate ambiguities that may develop in the interpretation of the resulting data. The voluntary exchange of information related to the national use of all chemical explosives greater than 300 tonnes TNT-equivalent is an example of a suggested confidence building measure.

The sole purpose of an OS1 is to determine whether or not an ambiguous signal detected on the basis of the IMS data was generated by a nuclear explosion. Initiation of an OS1 will require a positive vote from 30 of the Executive Council's 51 members and will therefore be difficult to initiate, minimizing the number of such occurrences. If the OS1 is at a mine site, the mining company, cooperating with its government, will be asked to comply with the rules of inspection and facilitate the visit of the inspectors. These inspectors may deploy a variety of instruments and collect different types of samples. They may also want to drill into the subsurface. The actual and political cost of an OS1 will be great, thus making them infrequent.

MINING EXPLOSIONS

Types of Mine Explosions

Blasting operations in surface coal, open-pit operations, and underground operations have the highest potential of being detected at regional seismic stations of an IMS. Seismic visibility would increase proportionally as a function of hole diameter, bench height, explosive quantity per hole, number of holes fired per delay interval, the ground response to the explosion, and the total amount of explosive detonated per unit space and time.

Surface coal cast blasting requires heavy explosive loads where individual holes in a shot are fired instantaneously or with very short delays (under 25 ms) between them. Delays between rows of holes can range from 50 to over 250 ms. Powder factors can range from 0.17 to 0.87 kg of explosives per cubic meter (0.5 to 2.5 lb/yd3) of rock blasted, depending on the targeted final muckpile configuration.

In open-pit operations holes can be detonated individually, in combination, or simultaneously along a row of holes. Powder factors can range from 0.1 to over 0.67 kg/m3 (0.3 to over 2.0 lbs/yd3) depending on a host of factors ranging from the material hardness to the type of digging equipment used. The harder the material, the higher the powder factor which is required to fragment the material.

Underground blasting techniques are dependent on the same parameters as those described for surface operations, in addition to a heavy dependence on the exact nature, thickness and orientation of the ore body being mined. Only sublevel caving, longhole open stoping, and final pillar recovery in the room and pillar method represent a high potential of being detected at far-field seismic stations.

Ground Vibration and Airblast Monitoring in the Near-Source Region

Current ground vibration monitoring in mines and around blast sites is performed with relatively inexpensive seismographs. Most seismograph stations are located within a kilometer or two of the blasting operation, usually at some point of immediate concern. In any case, the majority of mines monitor seismic/airblast levels with as few instruments as possible while still meeting local ordinances, or state and federal regulations. These local recordings may be useful in answering queries about questionable events through the voluntary Consultation and Clarification process.

Anomalous Blasts

Anomalous detonations of large amounts of explosives at the same time have been detected at regional seismic stations. They can occur in both surface and underground operations as a result of: direct and indirect lightning strikes; sympathetic detonations whereby a large number of holes or sections of a shot fire prematurely and instantaneously; accidents from improper use of explosives and failure to comply with the safety regulations; or operator errors and/or inexperience in designing and hooking up the shot sequence. These mishaps occur more frequently than one might think (approximately one of every 20 heavily instrumented shots are estimated to show such effects, F. Chiappetta, personal communication).

Regional Signals from Mining Exdosions

Seismic data at near-source distances are consistent with regional data, suggesting that contained nuclear explosions cannot be distinguished from contained chemical explosions that are simultaneously detonated (Denny, 1994). Mining and construction explosions that have characteristics similar to large, simultaneously detonated chemical explosions could be problematic in the context of monitoring a CTBT. The degree to which mining explosions will be of interest to the CTBT verification process will depend on the visibility or size of the signals and the degree to which the character of the signal reduces ambiguity with a nuclear explosion. In what follows, we first discuss the coupling of mining explosion to regional seismic waves affecting their visibility. This is followed by a discussion of techniques to uniquely identify the signals as being a legitimate mining explosion.

Mining explosions, as illustrated, are rarely detonated simultaneously, often emplaced in relatively incompetent near-surface layers and designed to fracture and/or cast the materials in which they are detonated. All these characteristics result in a reduction in amplitude relative to a contained, single detonation. Comparison of contained single-fired explosions to large delay-fired cast blasts in the same geology suggests coupling differences between the two source types that are frequency dependent. Coupling differences as small as a factor of 10 (contained shot more effective coupling) at long periods and as great as a factor of 100 at high frequencies have been observed.

Some of the largest operations in the blasting community involve the emplacement and detonation of explosives to cast the overburden rock into the pit and expose relatively shallow coal seams. This type of blast does not produce the distinctive impulsive character in the radiated compressive energy noted for fragmentation shots. Further, the long duration of cast blasts produce distinctive regional signals compared to a single-fired explosion.

Open pit fragmentation explosions designed to fragment hard rock for mineral excavation and recovery form a second subset of the possible types of explosions that will have to be identified. The blasting patterns tend to be simpler than those in cast blasting; such as by using simultaneous detonation of rows. The resulting banded nature of the regional seismic data provides a good discriminant from a singly detonated explosion. The fact that the amplitudes for a particular type of blast are similar to one another despite spanning large ranges in yield, illustrates that normal blasting operations designed to minimize in-mine motions will likewise minimize the amplitude of signals recorded at regional seismic stations. By implication, problematic blasting practices from the perspective of the mine operator will also be a problem in regional CTBT monitoring as the events can be large and with anomalous signal character, possibly similar to a small nuclear explosion.

GROUND FAILURES IN UNDERGROUND MINES

The Pervasiveness of Ground Failures

Underground mine failures that may produce regional seismic signals can be categorized as follows: planned failures which are controlled (blasting of existing pillars to create a mass of rock rubble); planned failures which are not controlled (initial and subsequent caving behind a new longwall in coal); and unplanned failures (pillar failures, coal bumps, and rockbursts).

Seismic Signals from Entineered CollaDses

Many mining techniques (e.g. longwall mining, block caving, pillar robbing or blasting) leave the roof unsupported and expect collapse as a result. These types of ground failure events typically produce seismic magnitudes less than 3.5. Details of three engineered collapses provide a quantification of this source type: the White Pine copper mine, in Michigan (room-and-pillar); the Twentymile coal mine, in Colorado (longwall): and the Henderson molybdenum mine, in Colorado (block-caving).

At the White Pine Mine, 72 pillars, each with an average cross-section of 74 m^2 were fragmented using a delay-fired sequence of 325 ms and using 59 tons of explosives. Near-source monitoring of the induced mine collapse showed that the individual explosive charges emplaced in the pillars did not produce strong seismic signals; however, the failure of the pillars and of the material above the working level did produce regionally detected signals. A regional magnitude upper bound estimate of 3.1 was determined for this event.

At Twentymile Mine, the seismicity associated with the mining of a 25,000 m^2 new panel, in a 3 m thick seam, beginning with the "first cave" of the panel, and continuing with the monitoring of aftershocks and subsequent collapses was recorded. There were five events between magnitude 2 and 3. The larger seismic events emanating from this longwall mine have a point-source seismic mechanisms similar to the larger unplanned collapses (see below).

The Henderson Mine experiments provided an opportunity to observe seismic signals generated by a block caving collapse. Both the explosion and caving events were quite small (M2) and likely would not be detectable by the CTBT monitoring system. The seismic events associated with this process are deficient in high frequencies compared with similar sized earthquakes

Seismic Signals from Unplanned Collapses

Some of the largest seismic signals associated with mining activities (M>3.5) are due to accidental failures in mines. Several have been documented in the U.S., and they have reached magnitudes as large as M_L=5.2 i.e. the 1995 Solvay Mine collapse in Wyoming. Specific discussion of two case histories are included: a coal mine at Gentry Mountain, Utah, and the trona mine of Solvay Minerals, near Green River, Wyoming. Careful analysis of the regional seismic signals from this class of events suggests a pattern of behavior similar to earthquakes for some seismic measures and similar to explosions for others. The current number of known collapses that have been studied is limited and more work needs to be done in this area to define the seismic criteria for identifying collapses separately. Studies of the larger collapses may indicate a reasonable agreement between the area of collapse as measured by seismic moment and that observed geodetically.

Seismic Signals from Coal Bumw and Rockbursts

Coal bumps occur frequently in the U.S. and in other countries such as India, Poland and South Africa. The most seismically active coal districts in the U.S. have been in Kentucky and Utah. Seismic evidence from large coal bumps in Kentucky indicates that they have similar source mechanisms to the large unplanned collapse events discussed earlier. Further research is needed to understand the precise mechanism of the failure generating the coal bump signals. While little work has been performed to identify and discriminate these events, on the basis of their mechanism and shallow depth we suggest they will have a behavior similar to that of the large collapse events.

The largest rockbursts (possible magnitude in excess of 5) have historically been related to shear motion on faults occasioned by mining. Most rockbursts are thus earthquakes and would not be expected to cause false alarms. However, some rockbursts are similar to implosional or explosional events and thus could be of concern to CTBT verification.

RECOMMENDED MEASURES TO REDUCE VISIBILITY AND AMBIGUITY

Measures Concerning Explosive Usage Visibilitv and Transparency

Comparison of near-source and regional waveforms from individual mining explosions has shown that practices designed to control ground motions in the strong ground motion region around the mine also control motions at regional distances. Poorly controlled shots are empirically found to be the ones that produce anomalously large regional amplitudes. Further, predictability of regional amplitudes from mining operations is apparently dependent upon the type and style of blasting. There are three major parameters which can significantly affect ground vibration amplitudes: the amount of explosives per delay, the delay period, and the detonation firing-time accuracy.

Reducing the amount of explosive detonated per delay is perhaps the single most important factor controlling ground motion. A 20% to 50% reduction of the explosive would be required before measurable reductions in vibration levels can be realized. Sizable reductions in the explosive weight per delay can be achieved by smaller borehole diameters, smaller bench heights and hole depths, multiple explosive decks within a single borehole, decoupling the explosive charge from the borehole wall, more stemming, and less subgrade drilling.

The delay periods used in blast designs can significantly influence the vibration outputs in terms of the amplitude and predominant frequencies. One of the ways for mine operators to determine the best possible delays in a shot is by performing a single hole signature analysis. By minimizing undesirable vibration in the near-field, these techniques have been shown to reduce vibration at the far-field regional stations.

The accuracy of pyrotechnic detonators has in general been steadily improving, but there are definite limits as to how far these improvements can advance. Precise, programmable electronic detonators hold considerable promise in the control of blast induced ground vibrations by eliminating the inherent scatter in pyrotechnic detonator firing times and providing unlimited choice of delay intervals.

A number of characteristics observed in the regional seismic data are proving to be useful for the purposes of identifying (or characterizing) a signal source as a standard mining explosion. When an explosion performs as designed, the resulting seismograms contain the effects in the frequency domain which are indicative of delay-firing. Time varying spectra often exhibit well defined constructive and destructive interference effects (modulation), called spectral scalloping.

One unique physical characteristic of cast blasts is their scaling of shot duration with total explosive weight. Long period energy around 10 s has been observed propagating from cast blasts. These seismic waveforms could prove to be characteristic of large, long time duration cast blasts.

Recent studies have shown evidence that mining explosions (and theoretically, mine collapses) register very large and characteristic signals at infrasonic stations. One of the biggest differences between a possible nuclear test and a mining explosion is that, in all likelihood, a nuclear test will be conducted underground to eliminate or minimize the release of radioactive materials or gas into the atmosphere. Much work remains to be done in assessing the utility of combined acoustic and seismic data sets for identifying mining explosions, but preliminary work suggests a possible synergy of the two technologies for source identification.

Measures Concernig Ground Failures

Three different approaches to mine design are described to reduce the risk of violent pillar collapses (Cascading Pillar Failure - CPF), namely 1) containment of failure, 2) prevention of failure, and 3) full extraction mining. The containment approach limits the spread of a potential CPF with barrier pillars. This approach is a noncaving room-and-pillar method that uses low width to height (W/H) ratio panel pillars surrounded by high W/H ratio barrier pillars. The prevention approach “prevents” CPF from ever occurring by using panel pillars with proper mechanical characteristics. The prevention approach is another noncaving room-and-pillar system; however, it uses high W/H ratio panel pillars and optional barrier pillars. The full extraction approach avoids the possibility of CPF altogether by ensuring complete opening closure (and surface subsidence) upon completion of retreat mining.

By-and-large, the reduction of coal bump and rockburst occurrences is an on-going endeavor in many countries including the U.S.; it is as much an art as a science. There is no clear-cut solution to the problem. Clearly, mines that reduce their unplanned collapses . cannot but enhance the safety of their operations.

Cooperative Measures for Calibration

Keys to the success of any monitoring system are the location and identification of the source of the seismic waves. Empirical procedures are suggested for calibration or fingerprinting of signals from active mines in order to minimize the impact of the verification system on mine operations by minimizing false alarms. The approach to obtaining ground truth information for calibration/validation of a regional monitoring system is to use a set of simple portable instruments which could be deployed and operated by one or two people with a minimum of effort in the near-source region. This approach would provide a cost effective methodology for calibration, using sources of opportunity such as those available in an active mining region. Near-source data gathered by this calibration system can also be used to assess important source processes that lead to regional signals that will be detected by the International Monitoring System.

POTENTIAL BENEFITS

Benefits to Industry

Utilization of data collected and techniques developed to assess and understand mining explosions for CTBT monitoring purposes provide the additional opportunity to address problems of direct interest to the mining industry, particularly in the areas of assessment of blast performance. Determination of differences between designed and actual detonation times is critical for control of in-mine ground motion as well as proper fragmentation and cast of material. A number of tools have been developed for the assessment of these effects including high speed film, video with de-interlacing and interpolation, ground motion measurements, velocity of detonation measurements in the explosive boreholes and connection of shock tube from the downhole delay to the surface.

Integrated data sets from explosive sources can also be used to assess the coupling of seismic energy by explosive sources. Visualizations, animated in time, can be used to identify how the explosive sequence rogressed and the effect on the amplitude of the near-source wavefield. Development of physical models of the blasting process can be used to help assess new blasting techniques. A variety of physical models of blasting are being developed that provide an improved and more comprehensive understanding of the physics, mechanisms and factors influencing mine-generated seismic disturbances.

Benefits to CTBT Monitoring

For the CTBT verification community, reducing ambiguity of detected signals through information exchange and research has many benefits including: (1) Unambiguously identified mine blasts can provide calibration for a number of important seismological measures such as phase identification, travel time, and amplitude decay rate; and (2) A more complete listing of the number and sizes of seismic events generated by mine blasting and ground failures will allow the CTBT monitoring community to better assess the number of false alarms caused by mines and will help prevent OSI's from potentially being called on legitimate mine operations.

The verification system will be more effective if the number of false alarms is kept to a minimum. A call for an On-Site Inspection will come at great economic and political cost, particularly if the event of concern proves not to be a nuclear explosion. For this reason, the detonation of single-fired, contained explosions in the same geology as that where standard delay-fired mining explosions are conducted can provide relevant empirical data for identifying differences between standard mining explosions and those that are simultaneously detonated.

Thanks to the cooperation of several U.S. mining companies, cost-effective techniques for conducting these calibration events are being developed. These techniques can be executed in areas that prove to be problematic from a false alarm perspective, so as to improve event identification.

FUTURE TRENDS AND OUTSTANDING ISSUES

Evidence exists supporting the contention that typical mining explosions couple energy into the seismic wavefield far less efficiently than a contained explosion, such as a nuclear test. These coupling differences are probably a function of the frequency of the observed seismic waves as well as of the particular blasting practices employed. These require further documentation and quantification.

Source models exist for earthquakes and explosions that allow one to assess the area or volume of the source region as well as the amount of displacement in the source region from a seismic signal. Development of similar models for ground failure in underground mines is needed.

Models that include the important source phenomenology of mine explosions such as shock coupling, spall, and material cast need to be developed and refined. These models should utilize both the regional seismic signals that these events generate as well as close-in observations of the phenomena in the mines.

Analysis of infrasonic signals with an emphasis on differences from nuclear tests may provide additional tools for reducing the ambiguity of mine-related signals. The synergy of infrasonic data in combination with seismic data may be very important.

Consideration of similarities and differences of U.S. mining practices with those used internationally is needed. New technologies must be assessed as they are introduced. One technology that is in the process of being introduced is electronic detonators with precise initiation time control.

The Comprehensive Test Ban Treaty has been successfully negotiated and awaits ratification and entry into force. Implementation of the treaty will require the resolution of many issues such as, the format of an on-site inspection; how questionable or ambiguous events will be handled; and what will constitute a questionable or ambiguous event. The results of research conducted in cooperation with the U.S. mining industry have identified a number of practices and tools which, if widely adopted and practiced, would likely reduce the false alarms that may be registered by an International Monitoring System.

REPORT ORGANIZATION

This report focuses on two general classes of mining events that will generate regional seismic signals. In Chapter 2 (Mining Explosions) explosion sources are discussed from both the perspective of the mine operator in the near-source (within the mine) and the regional observations. The link is made between blasting practices in the mine and the resulting regional seismic signatures. Chapter 3 (Ground Failures in Underground Mines) focuses on ground failures in underground mines and their resulting seismic signatures. Characteristics and sizes of the regional seismic observations from these different source types are documented. Recommended measures for reducing the size of the regional signals from the different source types or assuring that the resulting signals are easily recognizable as mining related are discussed in Chapter 4 (Recommended Measures to

Reduce the Seismic Visibility and Ambiguity). Possible active procedures for assuring that no mining operation produces a signal that is questionable are addressed. The techniques and analysis tools that have been assembled to characterize the seismic signals from mining operations have intrinsic value for the mining industry, in addition to being essential for Treaty verification. These dual use items are discussed in Chapter 5 (Potential Benefits). Cooperation with the U.S. mining industry has been the central reason for success in the quantification of seismic issues associated with the monitoring of a CTBT. Chapter 5 also documents the benefits that have been gained by this interaction. Finally in Chapter 6 (Future Trends in Relevant Mining Activities, and Outstanding Issues) a list of outstanding issues is drawn and possible approaches to their quantification are documented. These issues should be addressed in the future, as CTBT verification is implemented.

Appendix C

Committee on Seismic Signals from Mining Activities

Thomas J. O'Neil is Executive Vice-President for Operations of Cleveland-Cliffs Inc; in addition he is President of The Cleveland-Cliffs Iron Company and Cliffs Mining Company. Dr. O'Neil is responsible for five North American iron ore mines, which are the leading supplier of high-quality iron ore products to the steel industry. He has a wealth of experience with many mining activities. Dr. O'Neil previously was head of the Department of Mining and Geological Engineering at the University of Arizona.

Thomas J. Ahrens is W. M. Keck Professor of Geophysics at the California Institute of Technology and was elected to the National Academy of Sciences in 1992. He organized, built, and directed the first academic laboratory in the United States devoted to understanding dynamic properties of earth and planetary materials. Dr. Ahrens has recently investigated the generation of shear waves from explosions in spherical cavities.

Catherine T. Aimone-Martin is professor and chair of the Department of Mineral and Environmental Engineering at New Mexico Institute of Mining and Technology. Dr. Aimone-Martin has served on the Board of Directors of the Society of Explosives Engineers. She authored the chapter on blast design of the *Society of Mining Engineering Handbook*. Dr. Aimone-Martin is a member of the U.S. National Committee for Rock Mechanics.

Robert R. Blandford was director of seismic research in the Alexandria Laboratory of Geotech Teledyne, Inc., and Program Manager for Seismic Research at the Defense Advanced Research Projects Agency prior to joining the Air Force Technical Applications Center as a Senior Scientist located at the Center for Monitoring Research where he performs research and works on technical aspects of policy issues related to the Comprehensive Test Ban Treaty.

Blair M. Gardner is the Assistant General Counsel and Director of Government Affairs of Arch Coal, Inc. Mr. Gardner is an attorney and is responsible for environmental and regulatory affairs related to mine operations.

Michael E. Karmis is professor and chairman of the Department of Mining and Minerals Engineering at Virginia Polytechnical Institute and State University. Dr. Karmis' expertise is in rock mechanics, particularly underground stresses and strains, mine subsidence, and mine design.

William Leith is a research geologist with the U.S. Geological Survey. Dr. Leith is Chief of the Special Geologic Studies Group, which specializes in geologic studies of foreign countries, including work related to the monitoring and verification of the Comprehensive Nuclear Test Ban. Much of his recent work has concentrated on mining-related seismology in the former Soviet Union.

Jean-Michel M. Rendu is Vice President for Resources and Mine Planning, Newmont Gold Company; Dr. Rendu was elected to the National Academy of Engineering in 1997. He is expert in optimizing mine operations. Recent interests include effective transfer of advance mining technology in remote parts of the world.

John E. Wiegand is president of Vibronics, Inc. in Evansville, Indiana. Mr. Wiegand specializes in blasting seismology and vibrational effects. He previously worked for the state of Indiana as a mine inspector and blasting specialist.

Zavis M. Zavodni is Chief, Geotechnical Engineer with Kennecott Utah Copper. Dr. Zavodni is an expert on geomechanics and slope stability, a major factor in design of rock blasting.