11 Comprehensive Nuclear-Test-Ban Treaty and U.S. Security

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Summary

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) offers a significant opportunity toward implementing President Ronald Reagan's vision of establishing a global verification regime for nuclear weapons. A review of the past decade's developments shows that i) the CTBT is effectively verifiable, ii) it does not undermine the U.S. ability to sustain a nuclear deterrent, and iii) its entry into force would enhance the United States' security by constraining development of the most destructive weapons known. The latter conclusion is not new, but is stronger in the post-9/11 era that identifies radical terrorism as one of the gravest threats to national and international security. Additional steps for the U.S. to pursue in order to increase its security include: 1) Initiating an informed domestic political dialogue leading to CTBT ratification; 2) Reinstating full funding supporting the CTBT Organization; 3) Enhancing international transparency and confidence-building measures associated with sub-critical experiments and other aspects of nuclear weapon stockpile stewardship; 4) Establishing a periodic review of the CTBT, to be based on information from the national laboratories (and other sources) but led by an independent entity commissioned by Congress; and 5) After ratification, taking the lead in bringing about the treaty's entry into force.

Table 1 Objections to Ratification*

Too little time for debate
Utility questioned
For abolishing nuclear explosions
For advancing nuclear non-proliferation
Concern about ability to maintain U.S. nuclear arsenal
Verification questionable

*Based on October 7, 1999, Statement of Senator Richard Lugar

Introduction

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) is intended to constrain the development and deployment of new nuclear weapons worldwide by prohibiting nuclear explosion tests that are used to validate weapon designs and advance weapons science. The Treaty was opened for signature on September 24, 1996, and has been ratified by 140 nations as of September 2007 (e.g., www.ctbto.org; Medalia, 2007a). Through a vote on October 13, 1999, however, the U.S. Senate declined to give its advice and consent to the Treaty's ratification, and the CTBT's entry into force awaits ratification by nine key nations including the United States.

The Senate debate preceding this vote was informed by testimony from a number of military, political, and technical specialists, including the directors of the three nuclear weapons laboratories (Los Alamos, Lawrence Livermore, and Sandia National Laboratories). Key issues at the time included (1) whether the United States can sustain its nuclear deterrent under a CTBT; (2) whether the Treaty is effectively verifiable; and (3) whether it serves U.S. security interests (Table 1). Subsequent to the vote, two of the most detailed studies of the CTBT's implications for U.S. security, by former Chairman of the Joint Chiefs of Staff, General (ret.) John Shalikashvili (2001), and by the National Academy of Sciences (NAS) (2002), specifically considered these issues.

The present paper reviews developments over the past decade, and

Table 2 Accomplishments of Stockpile Stewardship

Successful annual assessments of stockpile
Successful life-extension programs of weapons
Successful re-establishment of pit production
Retention of core capabilities
Advances in understanding weapon performance
Advances in understanding materials
Developments at experimental facilities
Implications of Future Planning

re-examines the Shalikashvili and NAS reports: Have their findings and conclusions stood up over time? Have new considerations come into play, and is there any indication whether potential benefits of a CTBT have increased or decreased in the past ten years?

Sustaining the U.S. Deterrent

The modern Stockpile Stewardship Program was initiated in 1994 to sustain the U.S. nuclear arsenal without nuclear explosion testing; its long-term success was therefore not well established at the time of the Senate debate on CTBT. Building on almost 40 years' prior experience with surveillance and refurbishment, the past decade's successes have clearly demonstrated the effectiveness of stewardship during a nuclear-test moratorium. This conclusion is documented by at least five developments since the program's inception (Table 2).

Annual Assessment

The safety, reliability, and effectiveness of the U.S. nuclear weapons stockpile are assessed each year, with the technical need for nuclear explosion testing explicitly considered. Detailed information for this evaluation comes largely from the Department of Energy's nuclear weapons complex: especially from the three national laboratories responsible for design and certification, but also from Pantex and other sites where assembly, disassembly, and surveillance of weapons or their components take place. It is performed under the auspices of U.S. Strategic Command, however, which means that the assessment team is responsive to the military "customer" of the nuclear-weapons complex and can more objectively evaluate the national laboratories' work.

The result is an assessment that is—and is widely viewed as being—both technically sound and devoid of conflicts of interest. Indeed, the surveillance program has uncovered defects in stockpile weapons over the years, and these have been addressed. The fact that the stockpile has been certified to the president to be safe, reliable, and effective every year since establishment of the modern Stewardship Program, with no need for resumption of nuclear-explosion testing, is therefore a significant indication of the U.S. capability to sustain its nuclear arsenal during a test moratorium.

Life-Extension Programs

In addition to evaluating the state of the stockpile, stewardship addresses the need to periodically refurbish nuclear weapons as part of their ongoing maintenance. The design and military mission remain unchanged, but materials and components of the weapon may be changed out during these "life-extension" programs (LEPs). Most of the upgrades affect components outside the nuclear-explosive package, such as the arming, fuzing, and firing system, the idea being to sustain or even enhance safety, security, reliability, and ongoing maintainability.

A major challenge for life-extension is that a nuclear weapon is an aggregate of several sub-systems, such that any change to one part of the weapon has to be carefully vetted in order to ensure that no new faults or vulnerabilities have been introduced in the functioning of other parts. This is accomplished through an extensive review of the LEP, and certification of the refurbished weapon system before it is re-introduced into the stockpile.

Considerable research has gone into the first life-extension programs in order to assure their effectiveness and reliability, and the resulting certification of refurbished weapons (e.g., W87 LEP) is one indication of the success of stewardship. That a major new life-extension program is currently underway for the W76, which comprises the largest number of deployed warheads in the U.S. stockpile, testifies to the confidence that both the military and nuclear-weapons laboratories have in the process as well as products of LEPs (see p. 12 of Medalia, 2007b).[1]

Pit Production and Certification

Another milestone of the Stewardship Program is the establishment of pit production at Los Alamos. The key component of the primary stage of a thermonuclear weapon, the plutonium pit, releases nuclear energy in response to the chemical energy of high explosives; it is the nuclear trigger for the secondary stage, which then releases the bulk of the weapon's yield.

Pits had been manufactured at the Rocky Flats plant until it was shut down for environmental violations in 1989. Re-establishing a capability to manufacture and certify pits for what is arguably the most sophisticated of U.S. weapons, the W88, was a significant challenge requiring thorough vetting. This validation has been accomplished through a combination of extensive scientific and engineering studies, including sub-critical experiments; the latter are performed at the Nevada Test Site, to allow dynamic studies of fissile materials, but they do not produce a nuclear yield (Jeanloz, 2000).

The fact that new manufacturing processes performed by new people could be successfully established in a new location is a clear indication of the robustness of Stockpile Stewardship.

1. "The W76 LEP that is currently underway is an excellent program in terms of technology, schedule, and cost. This LEP is successfully proceeding toward completion as of August 2008. I believe it meets the Navy's needs," said Dr. Barry Hannah, Branch Head, Reentry Systems, Strategic Systems Program, U.S. Navy (quoted in Medalia, 2007b).

Core Capabilities

More generally, the success of stewardship has rested on advances in the underlying understanding of weapons performance and materials. Cessation of nuclear-explosion testing has not caused the laboratories to lose technical competence, as had been feared by some when the Stewardship Program started. To the contrary, significant advances have been made as researchers were able to study the physics underlying weapon performance in great depth, undistracted by what had been the unrelenting demands of the nuclear-weapons program during the time of nuclear-explosion testing. Notable developments in understanding primary- and secondary-stage performance, as well as the link between the two, characterize the Stockpile Stewardship Program's first decade of accomplishments.

Recently completed studies of plutonium (Pu) aging are another illustration of the scientific capability that has been established under the Stewardship Program. Plutonium ages as do other materials, but it also experiences degradation due to its radioactive decay and consequent self-irradiation. Therefore, one must consider how pits within the stockpile may suffer from unanticipated degradation due to plutonium aging.

A five-year program of research by the Los Alamos and Lawrence Livermore National Laboratories documented that plutonium ages far more slowly than had been feared, and that the effective lifetime for the metal in U.S. stockpile weapons exceeds 80–100 years (Hemley, et al., 2007). This does not mean that aging of pits can be ignored, but that the timescale for monitoring degradation of Pu is long—decades or more—relative to the time periods required for decisions about the United States' future nuclear stockpile.

Arguably, more was learned during this five-year study period than had previously been known about plutonium. A notable component of the program has been the international engagement of scientists—from Russia (and, to a more limited degree, China) as well as Britain and France—in technical discussions about plutonium with U.S. scientists (e.g., Cooper, 2000; see also www.pu2008.org/). These unclassified discussions have helped to advance the science, and have also enhanced mutual confidence between technical communities in the different countries' defense and nuclear establishments.

Similarly, it would be useful for U.S. national laboratory researchers to publish in the international, peer-reviewed literature the (unclassified) details of how they ensure that sub-critical experiments truly have zero yield; that is, are not capable of sustaining a nuclear chain reaction. Computer simulations are performed ahead of time to determine that an experiment will not produce nuclear yield, even by accident, and measurements during the experiment verify that there has indeed been no yield. Describing these methods in the open scientific literature would do more than build confidence; it would also help establish what the U.S. means by a zero-yield criterion, by documenting how that criterion is met.

Returning to the Stockpile Stewardship Program, numerical simulation and experimental validation have provided the foundation for recent technical advances in understanding weapon materials and performance, and served well in attracting, retaining, and developing scientists and engineers at the national laboratories. Indeed, a case can be made that—supported by major advances in computational capability, and the establishment of such facilities as the Dual-Axis Radiographic Hydrodynamic Test Facility (DARHT) at Los Alamos and the National Ignition Facility (NIF) at Livermore—the U.S. is in a technically *stronger* position for maintaining its nuclear-weapons capability than had it continued with underground nuclear-explosion testing.

Retaining core capability in nuclear weapons is essential not only for responsibly maintaining the stockpile, so long as it is U.S. policy to have a nuclear arsenal, but also for reasons of threat evaluation, counterproliferation and counterterrorism around the world. For example, the national laboratories provide key technical support for the

IAEA and other organizations' inspection, treaty-verification and threat-assessment capabilities. They also have unique capabilities for developing new detectors, analytical methods (e.g., in nuclear forensics), computer algorithms, and other tools required for national and international security.

Future Planning

In addition to past accomplishments, a positive assessment of stewardship is strongly indicated by discussions of future activities being considered for the U.S. nuclear weapons programs. For example, the recently proposed Reliable Replacement Warhead program would leverage the capabilities established through stewardship in order to potentially deploy a new warhead without returning to nuclear-explosion proof testing (Medalia, 2007b). To be sure, the design would have to be closely rooted in the results of the U.S.'s 1000-plus nuclear tests. With no new military mission, and no need for nuclear-explosion testing, the new design would be an extension of the LEPs now successfully underway, focusing on enhancements in safety, security (e.g., preventing unauthorized use of the weapon), and maintainability.

It is not yet technically clear that the Reliable Replacement Warhead can be successfully realized, but the ability to consider the option in a responsible manner—with a strong scientific grounding—is in place (American Association for the Advancement of Science, 2007). Put another way, even contemplating such a possibility requires great confidence in the capabilities of the national laboratories and the nuclear-weapons complex, as they approach a generation's experience with stockpile stewardship under a nuclear-test moratorium.

In summary, the evidence from accomplishments of the recent past, as well as future activities being considered, clearly establishes that the U.S. is now able to sustain its nuclear deterrent without the need to resume nuclear-explosion testing.

Verification

The feasibility of monitoring nuclear-explosion tests, hence of verifying a test-ban treaty, has been of concern for many years, the issues being both political and technical (e.g., Gallagher, 1999). The focus here is on the latter, because high-confidence verification is impossible unless technical feasibility has been documented. From a technical perspective, effective verification means monitoring with high confidence that militarily significant nuclear explosions will be detected in a timely manner.[2]

The CTBT Organization's International Monitoring System (IMS) includes 321 seismic, hydro-acoustic, infrasound, and radionuclide stations, and 16 laboratories (Figures 1–5), and is due to be 90 percent complete at the beginning of 2009 (e.g., www.ctbto.org). The seismic, hydro-acoustic, and infrasound stations monitor sound waves transmitted through Earth's crust, oceans, and atmosphere, respectively, and provide estimates of the time, size, and geographic location of an explosion; they generally cannot distinguish a nuclear from a non-nuclear blast. In contrast, the gases and debris collected at radionuclide stations can prove that an explosion was nuclear, but do not in general resolve the time and location of the explosion to much better than a day and (part of) a continent. The seismo-acoustic and radionuclide methods are thus complementary.

Evidently, the IMS offers the capability to detect explosions down to yields of about 0.1–0.5 kiloton (kt) worldwide, identifying the character of the event as an explosion—rather than an earthquake, or an implosion as is the case for mine collapses (Richards, 2007)—as well as its time and location (see Figures 1–4 in color insert section after page 000). This raises two questions: (1) Is a fraction of a kiloton

2. After Testimony of Kathleen Bailey, former Assistant Director for Nuclear and Weapons Control, Arms Control and Disarmament Agency, in U.S. Congress, Senate Committee on Armed Services. *Comprehensive Test Ban Treaty.* S.Hrg. 106–490, 106th Congress, 1st Session, hearings held October 6 and 7, 1999, USGPO 2000, p. 201; see also Jonas (2007).

good enough for monitoring a CTBT that has a zero-yield threshold, and (2) How reliable are the estimates of monitoring sensitivity?

Utility of Monitoring with Low-Yield Threshold

Chapter 3 (and classified supporting material) of the NAS (2002) report addresses the first of these questions explicitly, distinguishing the benefits of testing at various yield levels either i) for nations with limited (or no) experience with nuclear-explosion testing or ii) for nations having significant experience with nuclear-explosion testing. The latter, for example, could use extremely low-yield tests to validate "one-point safety" of their existing designs, but this does not threaten U.S. security. More provocatively, the NAS group considered the possibility that a nation having considerable test experience could potentially get away with proof-testing a low-yield (1–2 kt) weapon if the blast can be effectively muffled ("decoupled"): a difficult task with significant probability of failure, that would in any case result in a design less-well validated than such nations already possess. The NAS (2002) study concluded that, though potentially politically significant, none of these scenarios poses new challenges to U.S. security from a technical perspective.

Similarly, a variety of scenarios could be considered for surreptitious nuclear-explosion testing by states having relatively little experience with nuclear weapons. In addition to their having far greater difficulty in preventing their test(s) from being detected, in comparison with nations having much more experience, such limited-experience countries may have less to gain from low-yield testing in terms of technical validation of their designs (NAS, 2002).

In short, being able to monitor a complete moratorium on nuclear-explosion tests to a fraction of a kiloton (tamped) yield has been found effective from the technical perspective of national and international security, but can one be assured that such sensitivity is actually in hand? The answer is yes, because the IMS provides only part of the world's detection capability, and this global capability has been—and continues to be—used, verified, and improved (e.g., Suda et al., 1998; Webb, 1998; Richards, 2007; Hafemeister, 2007).

Monitoring Sensitivity and Its Validation

i) Seismology and hydro-acoustics

The North Korean test of October 9, 2006 offers a case in point. This explosion was well recorded by the IMS, with 22 seismic stations (10 primary and 12 auxiliary) serving to locate the event to within the 1000 km^2 required by the CTBT, as reported in a Reviewed Event Bulletin of October 11 (CTBT Organization Preparatory Commission, 2007). It is also significant that many additional stations recorded the test, documenting its yield at about 0.5 ($\pm$0.3) kilotons, and validating that it was indeed an explosion, based on the small amount of shear relative to compressional energy released (see Figures 6–7 in color insert section after page 000). Nearby explosions carried out for scientific research on Earth's structure show that a test as small as 4–5 tons would have been detected at station MDJ (Figure 6, bottom), well below the 60-ton sensitivity expected for the primary IMS stations (Figure 2) (Kim and Richards, 2007; Richards, 2007).

Even a decade ago, at the time of the nuclear tests conducted by India and Pakistan, a seismic-detection threshold of less than 10–20 tons could be established from the noise level at non-IMS seismic stations recording those explosions (Barker, et al., 1998): again, much less than the detection limit for the primary IMS stations. As another example, the fact that the August 7, 1998, bombing of the U.S. Embassy in Nairobi, Kenya, was well recorded, with an amplitude corresponding to 4 ($\pm$2) tons of TNT, is an indication that even small blasts can be identified in completely unexpected locations (Koper, et al., 2002).

In comparison with these land-based explosions, sensitivity is far greater in the oceans. The explosions causing the Russian submarine *Kursk* to sink in the Barents Sea on August 12, 2000, were recorded at more than 20 seismic stations, located at distances up to 5000 km: a small blast—estimated at less than 20 kilograms yield—was discerned prior to the main explosion(s); the latter had a total yield of 4 tons and sealed the vessel's fate (Koper, et al., 2001; Savage and Helmberger, 2001). This seismological capability complements the high sensitivity indicated in Figure 4 for the hydro-acoustic system.

Such examples illustrate monitoring accomplishments over the past decade; but the actual capability at present and in the future is even better, if for no other reason than that deployment of modern, high-quality (e.g., broadband digital) seismometers continues at a significant pace worldwide. Only a fraction of that deployment is explicitly for CTBT verification, so it is important to recognize the complementary role played by the rest of the seismological community and by those utilizing national technical means in monitoring activity around the entire planet. Not only are more instruments becoming available for observations, but the underlying science is also experiencing dramatic advances.

One unexpected scientific development, for instance, is the recent discovery that horizontal variations in seismic-wave velocities throughout Earth's crust can be imaged from analyses of the ambient background noise recorded on seismometers (see Figure 8 in color insert section). The reason this is interesting is that the velocity heterogeneities act like lenses, refracting (bending) seismic rays and modifying the intensities of waves recorded at each seismic station. Therefore, it is useful to know the seismic-wave velocities throughout the crust in order to quantify seismic recordings of explosions (or earthquakes) at regional distances; that is, at ranges less than 300–700 kilometers, within which one can reliably detect small or decoupled nuclear tests. The noise-based method helps provide this information, with the potential of improving results beyond the current capability illustrated in Figures 6–7.

The background seismic noise is generated by storms, surf, and other ocean-atmospheric processes, to the point that the entire planet is constantly humming at the natural frequencies of Earth's acoustic harmonics (e.g., Webb, 1998; Rhie and Romanowicz, 2004; Gerstoft, et al., 2006; Shapiro, et al., 2006; Gerstoft and Tanimoto, 2007). The method amounts to correlating the background noise recorded at pairs of seismic stations, the correlated signal being sensitive to the wave velocities between each of the two stations. Tomographic analysis of the results, analogous to medical imaging by CT scan, produces the final images of wave-velocity variations (such as Figure 8), which can then be used in subsequent analysis of small events, whether earthquakes or explosions.

To be sure, noise-based tomography is not intrinsically better than the traditional methods of determining seismic-wave velocities between an earthquake (or explosion) and a seismic station. What the ambient-noise method offers, however, is important complementary information that helps to validate the results from traditional approaches, and to fill in the gaps where natural earthquakes or human-caused explosions are insufficient for determining velocity variations in a given region of the world (e.g., due to low levels of seismicity, or inaccessibility of a region of interest). Models of crustal seismic-wave velocities are thereby improved, to the benefit of the monitoring as well as the academic-research communities.

In the meantime, existing capability can also be made more effective. For example, one recommendation is to operate the IMS Auxiliary Network continuously as an enhancement to the Primary Network, thus improving detection capability and allowing supplementary stations to be used more easily to assist with identification of seismic events.

ii) Infrasound

Infrasound refers to low-frequency (0.001–20 Hz) acoustic waves in the atmosphere. This type of monitoring is less-well developed than seismology, but major advances are underway as more infrasound sensors are being deployed for the IMS than were ever available in the past. Many natural sources of infrasound are being documented, and a vibrant research community is establishing itself as experience is being gained from the deployed systems (e.g., Hedlin and Romanowicz, 2006).

For example, infrasound has recently documented the amount of meteorite and comet debris that continuously impacts Earth's atmosphere, showing that our planet experiences the equivalent of a 30-ton explosion twice a week, a 5-kiloton explosion about once per year, and a 10-megaton (Mt) explosion roughly once per millennium (Brown, et al., 2002; Edwards, et al., 2006, 2007). Many of these events are recorded by satellites designed to monitor Earth's surface for nuclear explosions, although the most recent known case of a 10-Mt comet- or meteorite-impact event is the Tunguska explosion that devasted more than 2,000 square kilometers of forest in Siberia on June 30, 1908.

Another notable example is the December 26, 2004, tsunami, which is estimated to have killed more than 200,000 people around the Indian Ocean (see Figure 9 in color insert section after page 000) (e.g., LePichon, et al., 2005; de Groot-Hedlin, 2005; Tolstoy and Bohnenstiehl, 2005; Satake and Atwater, 2007). It is now understood that many casualties might have been avoided if the combination of existing seismic, hyrdo-acoustic, and infrasound sensors had been coordinated into an effective tsunami-warning system: a task for which they were not designed (nor were there adequate means in place, at the time, to communicate such a warning). A tsunami warning system does exist in the Pacific, but such devastation was previously unanticipated for the Indian Ocean; elements of a warning system are now being deployed (e.g., Normile, 2007).

Other natural events being monitored by infrasound include explosive volcanic eruptions that can eject sufficient ash up to stratospheric heights to threaten commercial aviation (Garcés, et al., 2007). Experience being gained with these natural sources is helping researchers to better understand the propagation of sound waves through

Figures 1–10 for Chapter 11, "Comprehensive Nuclear-Test-Ban Treaty and U.S. Security" by Raymond Jeanloz

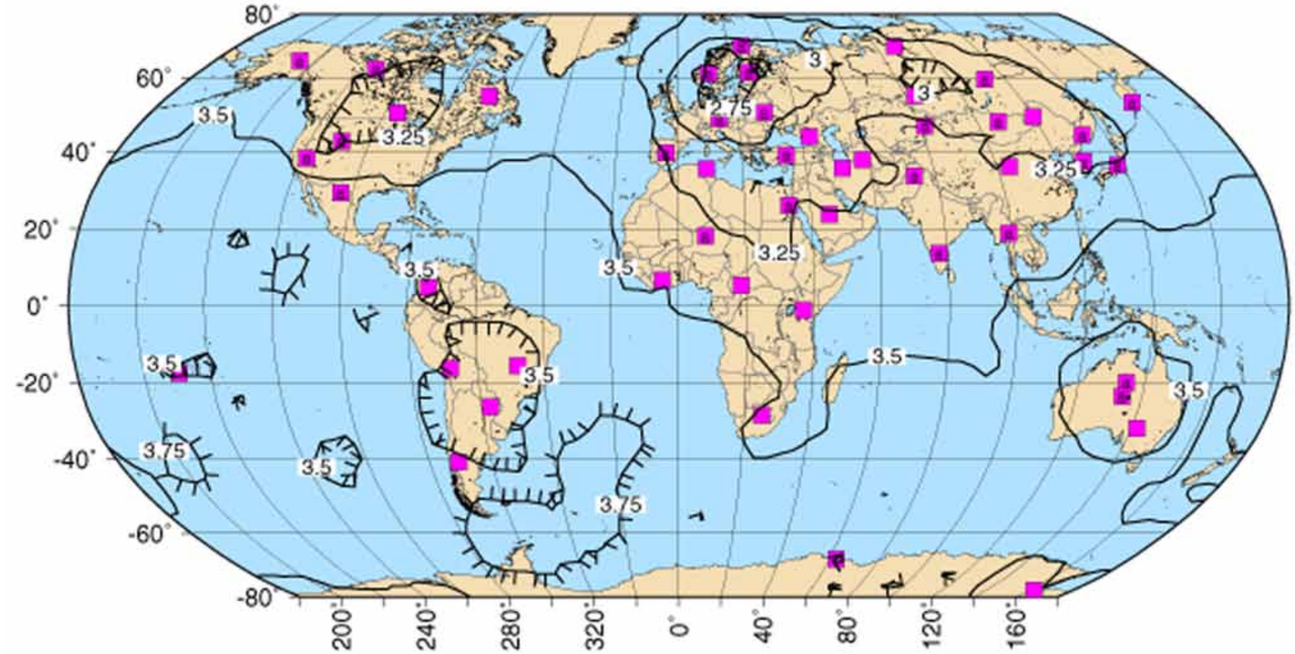


Fig. 1. Contours of seismic magnitude for which signals would be expected at 3 or more stations of the IMS primary seismic network (50 stations, shown as purple squares) from 90 percent of the events at or larger than the given magnitude. Contour interval is 0.25 magnitude units, and the detection threshold for Europe, Asia, North America and North Africa is in the magnitude range 3.0–3.5 or lower (from National Academy of Sciences, 2002).

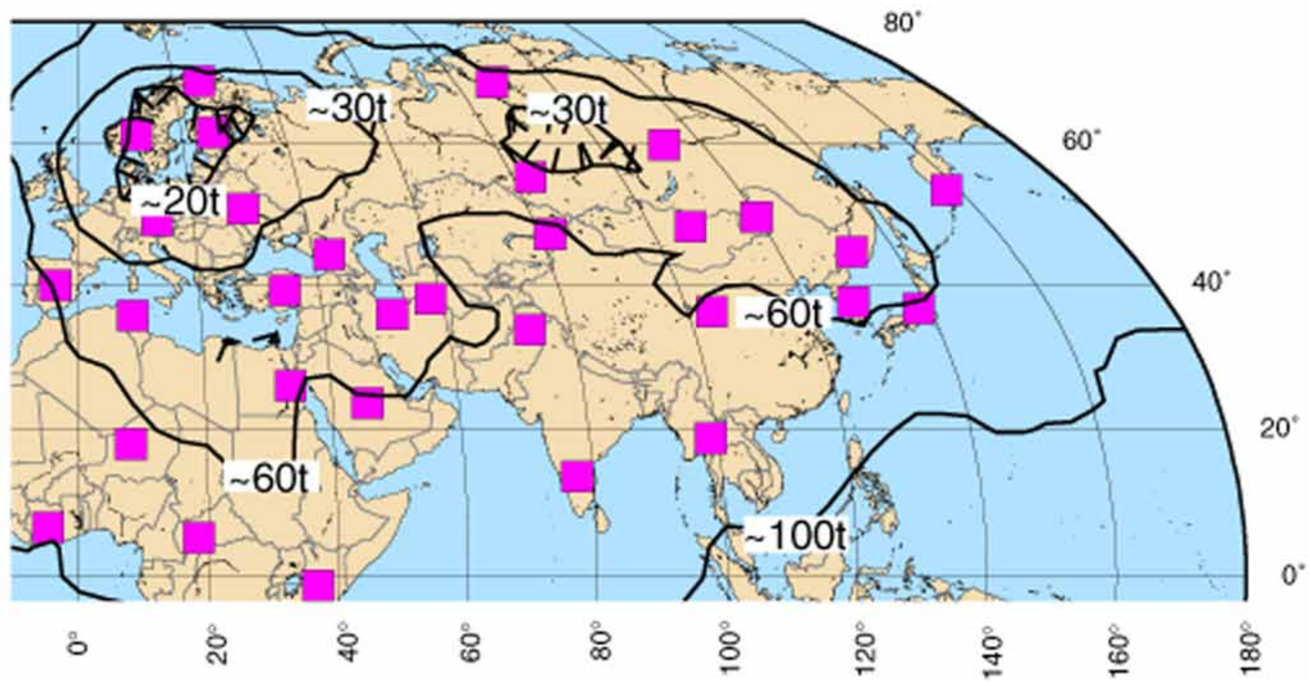


Fig. 2. Contours of approximate yield (tons = thousands of kilograms TNT equivalent) of tamped explosions, for which detections can be expected at 3 or more IMS primary stations (purple squares). These contours are the same as in Fig. 1, but with an expanded view of Europe, Asia and North Africa, and with seismic magnitude translated to yield (from NAS, 2002).

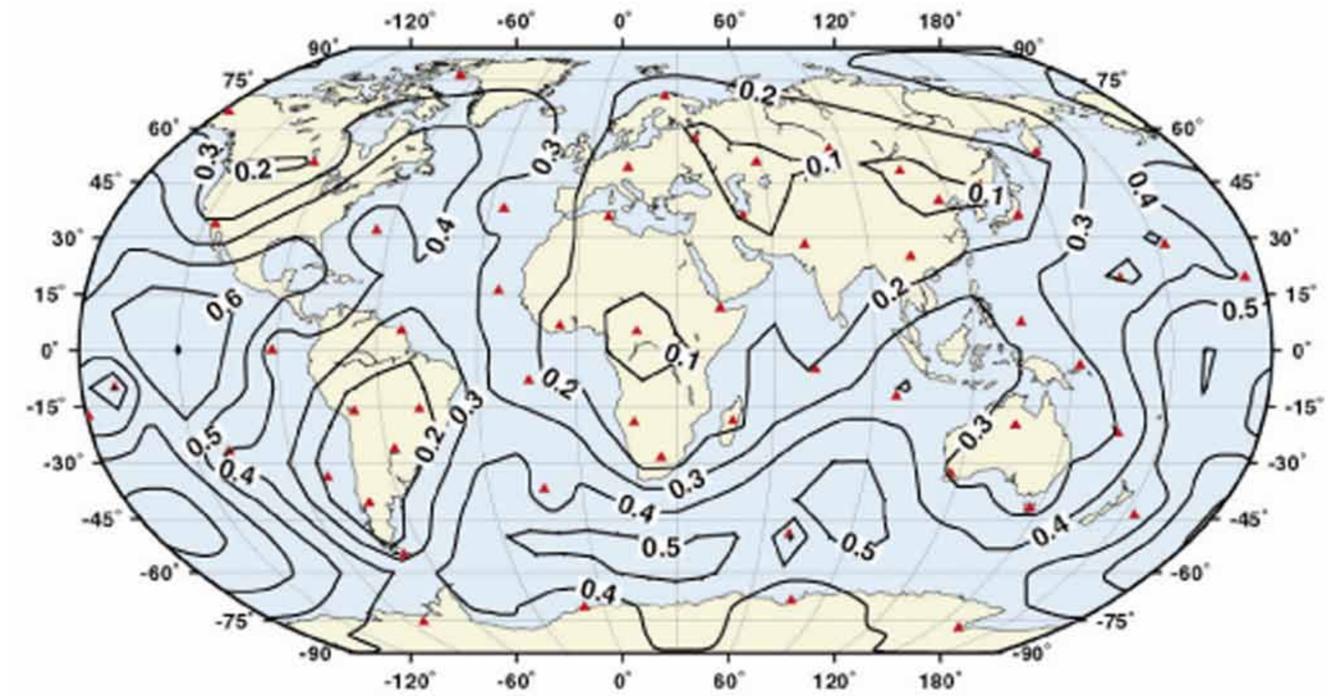


Fig. 3. Contours of yield (kilotons = millions of kilograms TNT equivalent) of atmospheric explosions that would be detected with 90 percent probability at more than 1 station for the planned IMS network of 60 infrasound stations (red triangles) (from NAS, 2002).

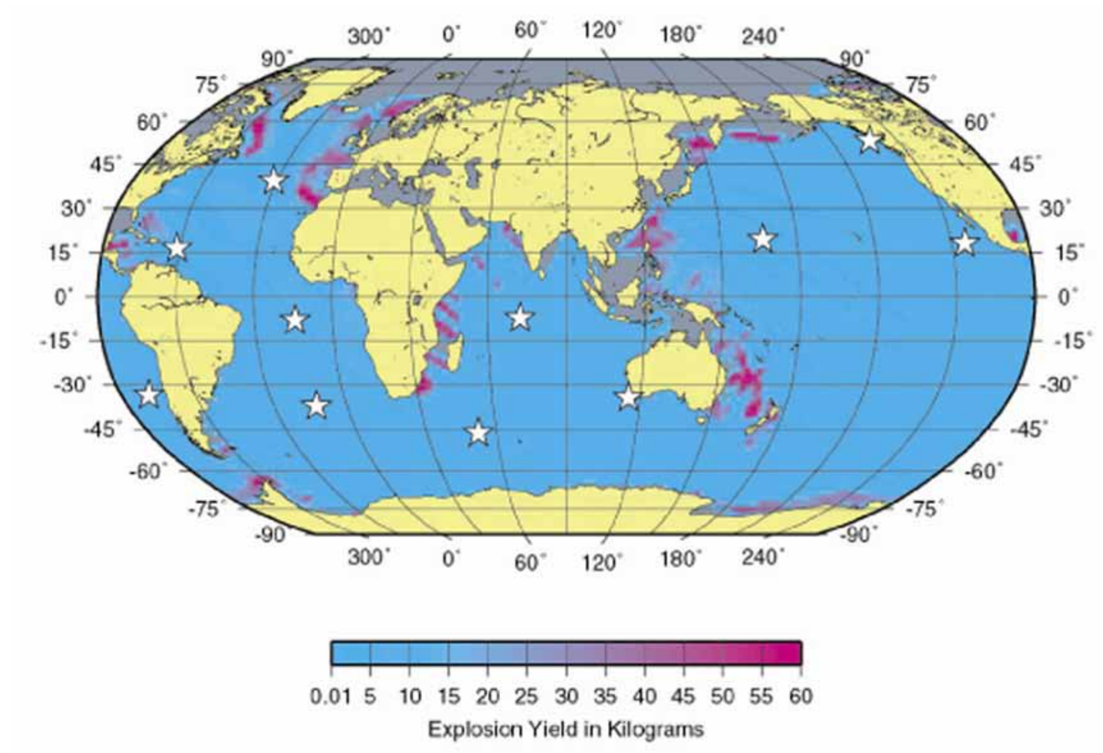


Fig. 4. Yields (kilograms TNT equivalent) of underwater explosions that would be detected with 90 percent probability at more than 1 station for the planned IMS network of 11 hydroacoustic stations (stars) (from NAS, 2002). The IMS is not intended to cover inland seas (grey), but the text provides examples of global monitoring capability in these regions.

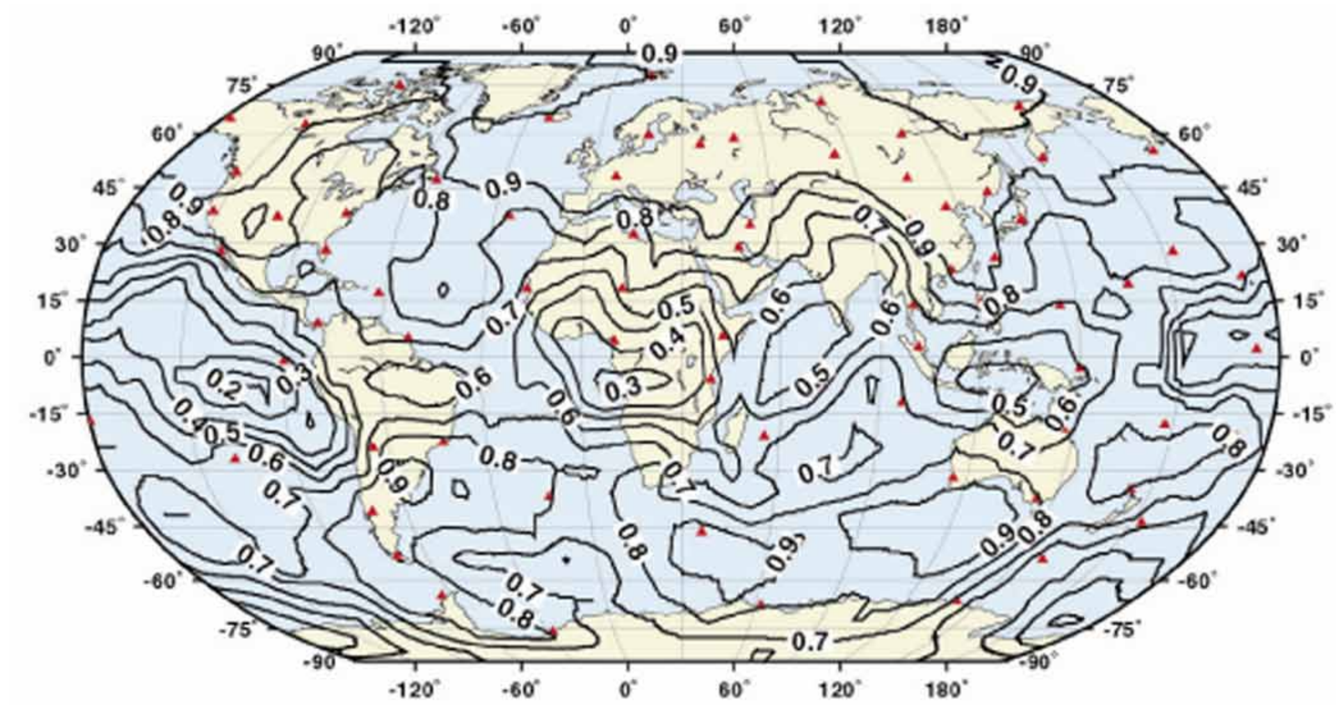


Fig. 5. Probability of one-station detection of a 1-kiloton nuclear explosion within 5 days by the planned 80-station IMS radionuclide network (red triangles) (from NAS, 2002).

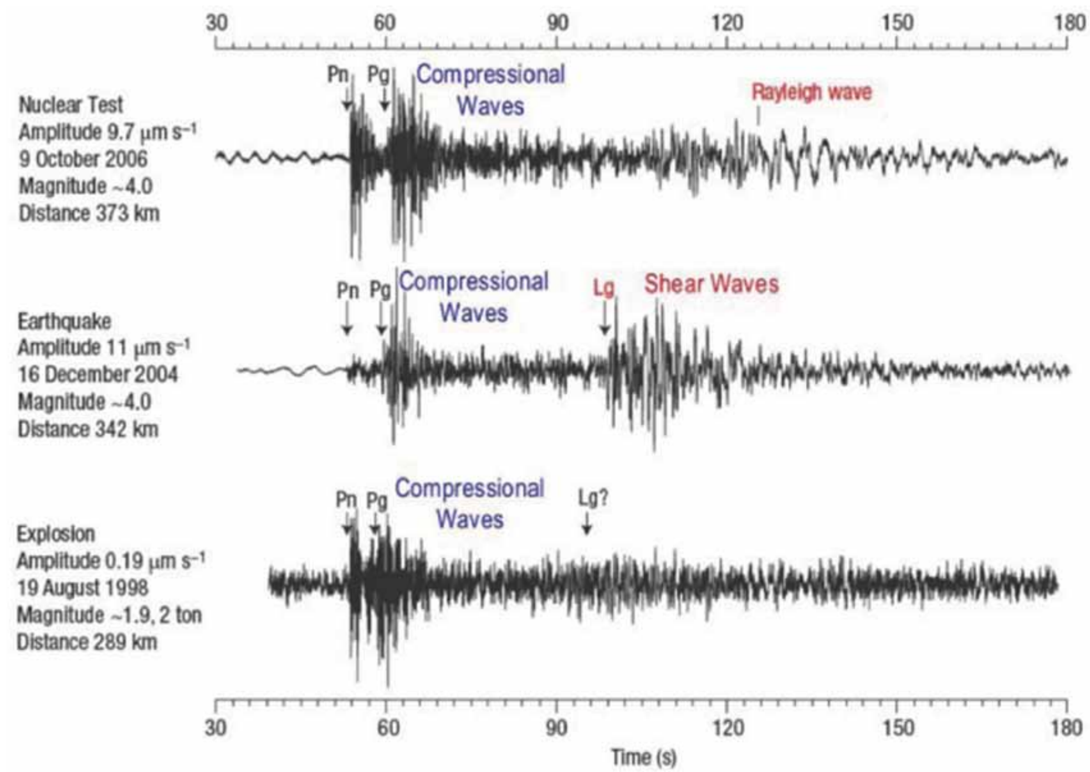


Fig. 6. Seismograms (vertical ground velocity as a function of time) of the October 9, 2006 North Korean nuclear test (*top*), an earthquake of magnitude 4.0 (*middle*) and an explosion of 2 tons of TNT (*bottom*) recorded at Mudanjiang, China (station MDJ, which is not part of the IMS). The explosions cause a sudden onset of compressional waves (including *Pn* that travels via the crust and mantle, and *Pg* that travels via the crust alone) and weak shear waves (including *Lg*); in contrast, compressional waves emerge more slowly and shear waves are stronger for the earthquake. After Richards and Kim (2007).

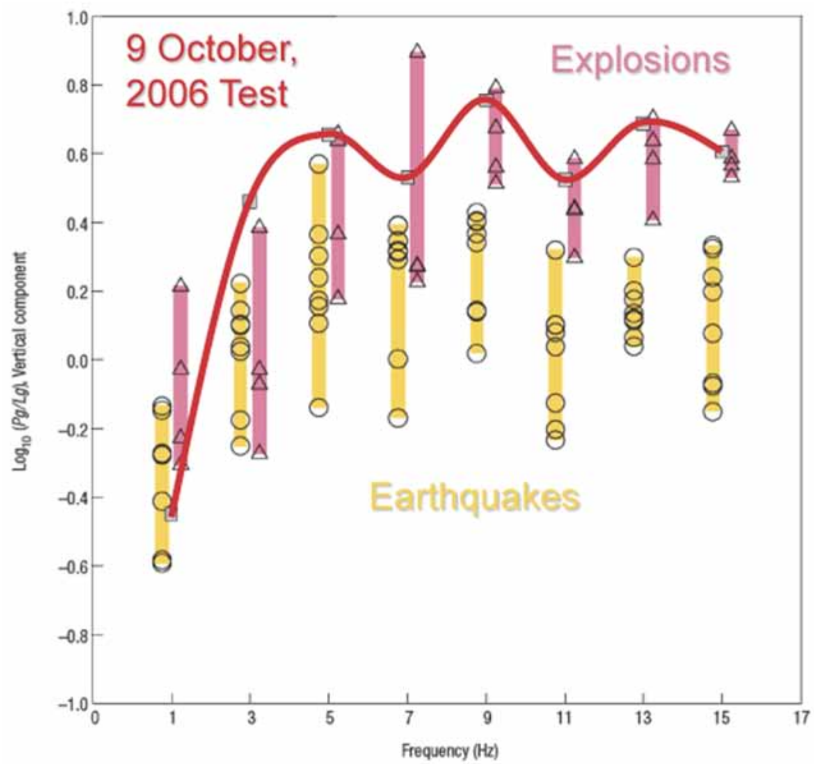


Fig. 7. Logarithm of the ratio of amplitudes of compressional (*Pg*) to shear (*Lg*) waves determined as a function of frequency from vertical-velocity recordings (Fig. 6). Explosions (triangles, full range marked in pink) consistently show higher values than earthquakes (circles, full range marked in yellow) at the higher frequencies, and measurements for the October 9, 2006 test (squares linked by red line) clearly fall in the range characteristic of explosions. After Richards and Kim (2007).

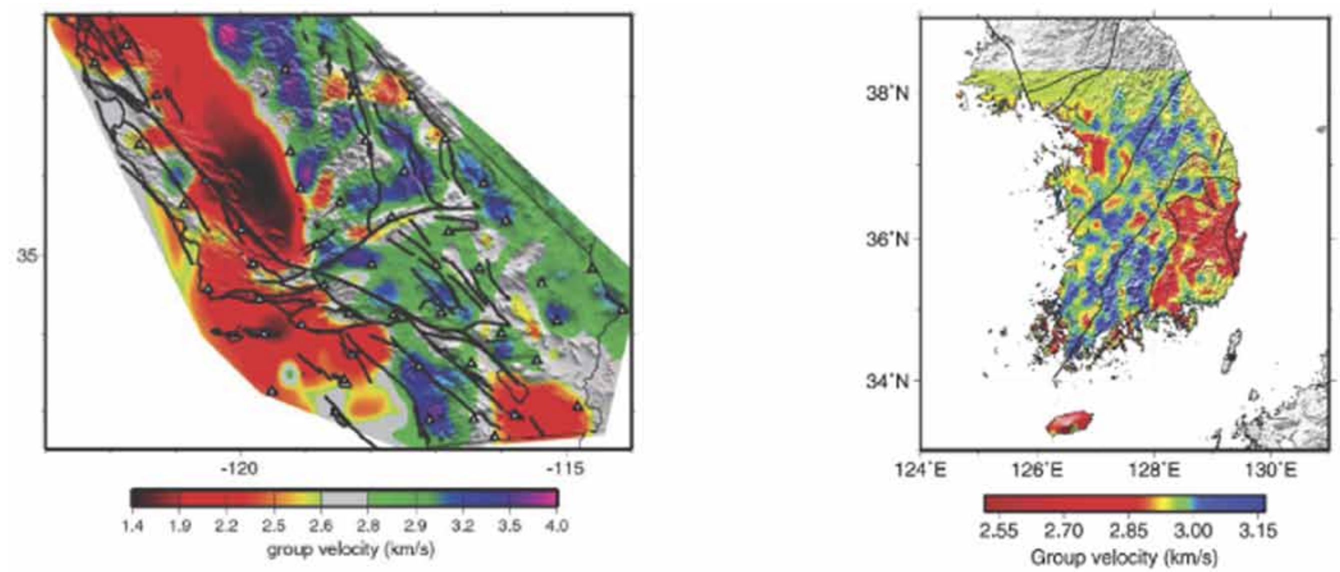
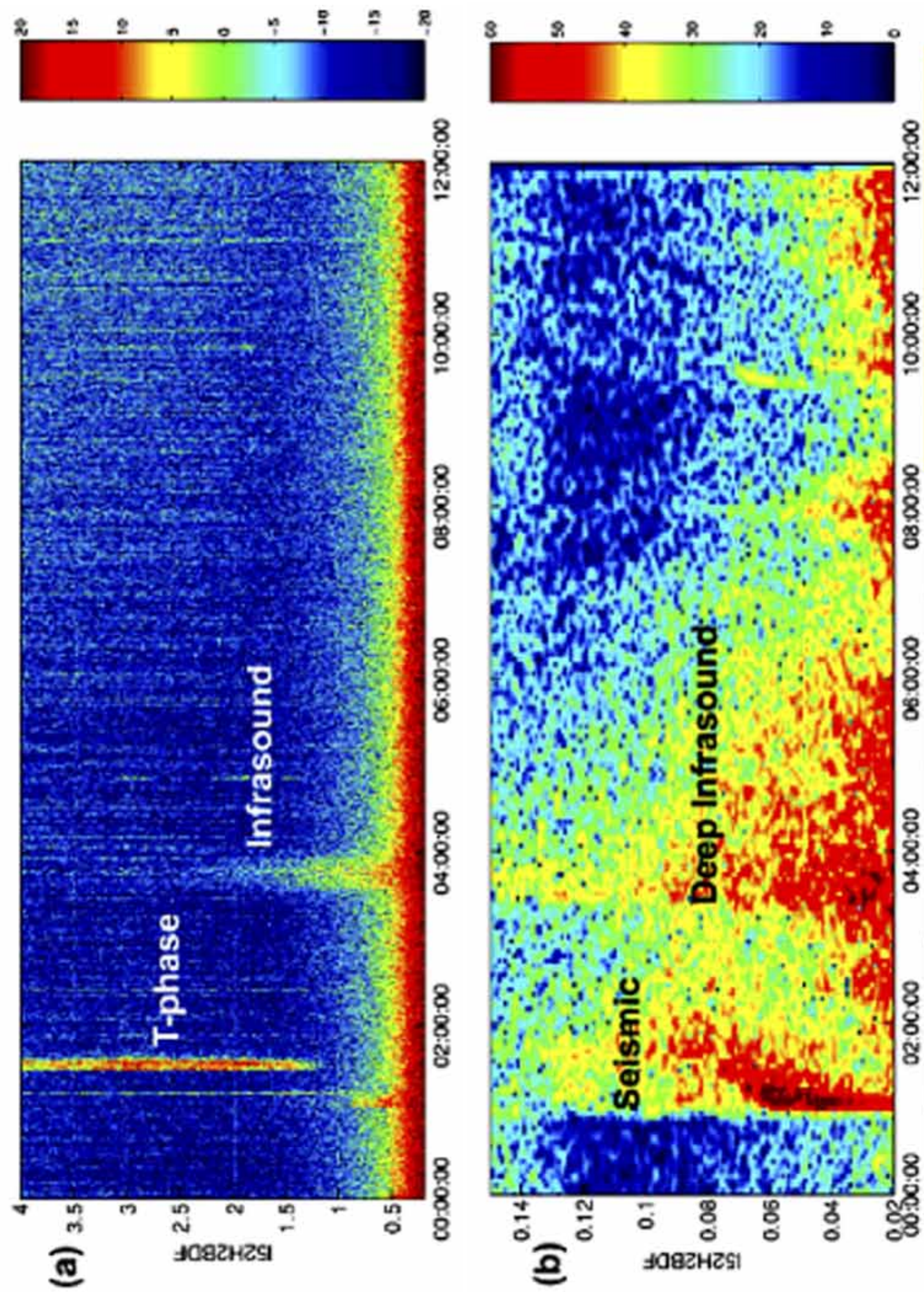


Fig. 8. Variations in velocities of seismic surface waves in Southern California (*left*) and South Korea (*right*) imaged using background seismic noise. Red and blue show velocities that are slower and faster, respectively, than average. As these variations effectively cause the observed seismic energy to bend, into fast-velocity and around slow-velocity regions, they affect the focusing of waves reaching each station. Understanding such focusing leads to more accurate locations, magnitudes and source mechanisms for earthquakes or explosions, and to enhancing the sensitivity of seismological methods. From Shapiro, et al. (2005), and Kang and Shin (2006); see also Sabra, et al. (2005).



(a)
I52H2BDF
T-phase
Infrasound
(b)
I52H2BDF
Seismic
Deep Infrasound

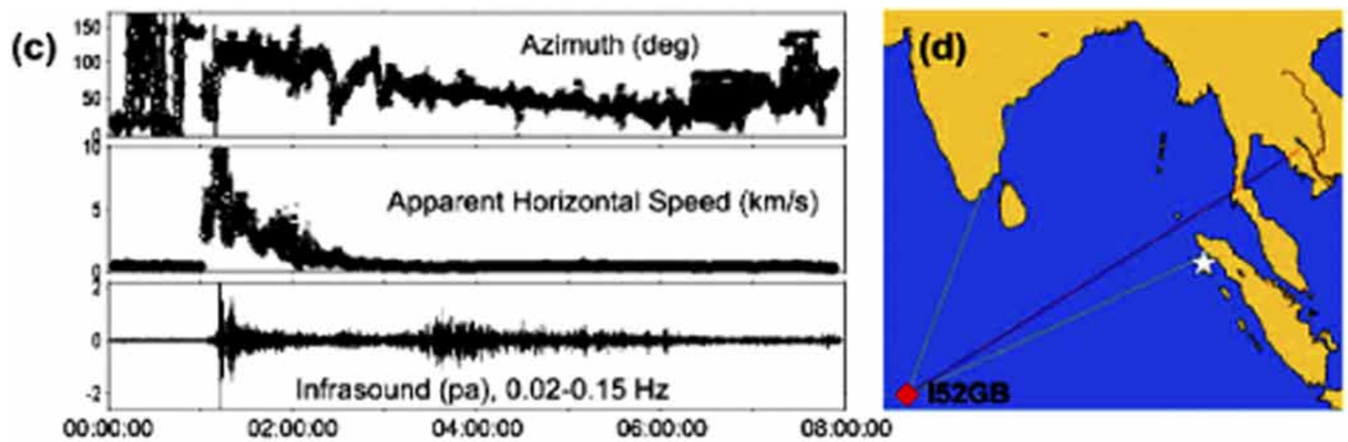


Fig. 9. Infrasound signal of the December 26, 2004 Sumatra earthquake and resultant tsunami, recorded 3000 km away at station IS52GB on Diego Garcia. (*a*) Spectrogram showing the frequencies between 0 and 4 Hz observed as a function of time, with detail between 0.02 and 0.15 Hz given in (*b*); (*c*) arrival azimuth (clockwise from north), apparent horizontal propagation speed across the array, and acoustic signature from the 0.01–0.15 Hz band; (*d*) range of azimuths inferred from array (see *c*), swinging from ENE to NNE (green lines) during the 4-hour record of infrasound, shown in comparison with locations of the earthquake (white star) and station (red diamond) (from Garcés, et al., 2005).

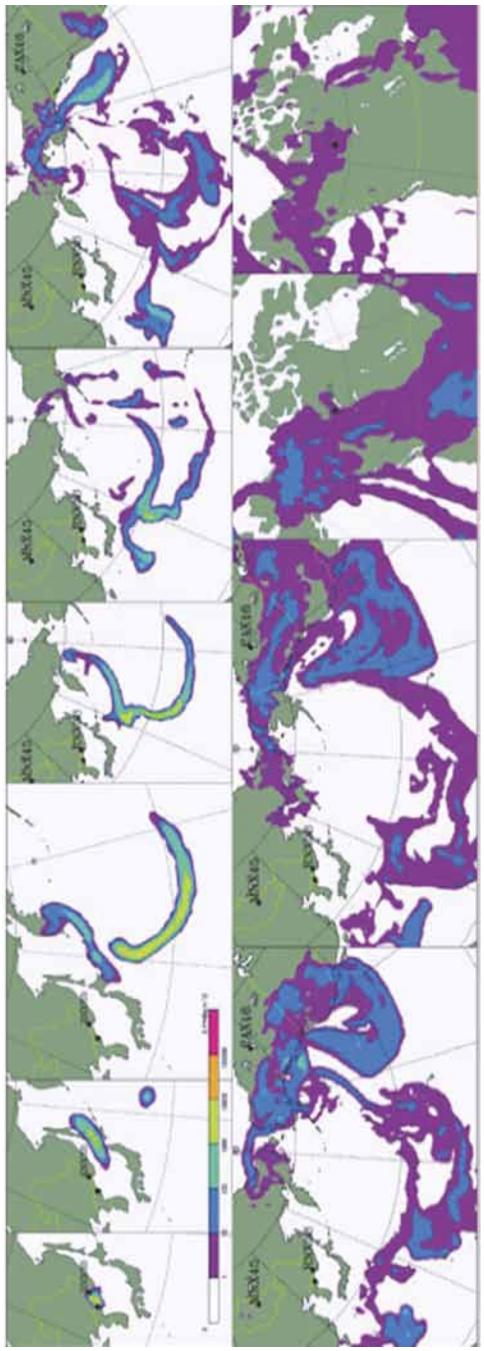


Fig. 10. Calculated location of ^{133}Xe plume generated by the Oct. 9, 2006 North Korean test, shown as a function of time from upper left to lower right as it reaches Canada. From Saey, et al. (2007b).

the atmosphere, thereby improving the ability to determine the location and size of an explosion recorded by infrasound.

In actuality, the situation is developing even more quickly than might have been anticipated, due to the fact that infrasound is now being recognized on recordings from broadband seismometers (e.g., Ishihara, et al., 2004; Langston, 2004; Cochran and Shearer, 2006; Edwards, et al., 2007). As seismometers are far more numerous and widely distributed than infrasound detectors, this means that many more observations of an event can potentially be made than from the IMS infrasound network alone. More experience can be gained, better atmospheric-propagation models developed, and—through engagement of the large seismological research community—scientific advances can be greatly accelerated. A related development is the recording of infrasound by Global Positioning System (GPS) receivers (e.g., Calais, et al., 1998), which again broadens both the technology and community involved with nuclear-explosion monitoring.

iii) Radionuclides

As with infrasound, radionuclide capability has improved significantly due to deployment of the International Monitoring System (Figure 5) and complementary stations. Remarkably, even the small (sub-kiloton) yield of the North Korean test released a noble-gas signal (^{133}Xe) consistent with a nuclear (as distinct from chemical) explosion, as reported from systems deployed in South Korea. In fact, a xenon-isotopic anomaly was predicted using advanced atmospheric transport models, and then detected at the Yellowknife, Canada, IMS station CAX16—more than 7,000 km away—12 to 18 days after the event (Figure 10) (Saey, et al., 2007a, b). It may not offer conclusive attribution by itself, especially as to location and time, but the signal is compatible with the North Korean event having been a nuclear test.

There remains considerable opportunity for enhancing the science and therefore the monitoring of radionuclides. Specifically, deployment of additional atmospheric-gas and aerosol stations for academic research, and further analysis and modeling of the measurements, could significantly expand current capabilities. Indeed, there is much scientific interest in improving this type of global atmospheric monitoring, and an enhanced capability could serve fields ranging from climate modeling to environmental monitoring.

iv) Satellite imagery

Finally, a significant resource that has emerged since the IMS was first being planned is the commercial availability of high-resolution satellite images. Such groups as www.isis-online.org/ and www.globalsecurity.org/ provide an important service in monitoring activities potentially related to nuclear-weapons development worldwide. Using commercial imagery, for example, D. Albright and P. Brannan of the Institute for Science and International Security have proposed an identification of the likely site of the October 9, 2006, North Korean test to within a few square kilometers. There can also be a close synergy between satellite and ground-based monitoring (e.g., Garcés, et al., 2004).

Moreover, evidence from imagery of preparations for nuclear-explosion testing can trigger special attention by IMS and non-IMS sensors, and quantitative analysis of images can place strong constraints on the likelihood that decoupling has been (or will be) attempted at a given site. New software tools such as those available at earth.google.com also facilitate the analysis and display of results.

Commercial imagery and private groups do not replace government analysts using national technical means, but do potentially offer greatly expanded capability in tracking activities around the world. In addition, they engage a large public community, thus decreasing the chances of surreptitious activity going unnoticed. It is also notable that commercial imagery can potentially be used to document conclusions reached on the basis of national technical means, thus making it easier to openly discuss government analysts' findings without revealing sensitive methods or capabilities.

In summary, the combination of national technical means, the International Monitoring System, and the academic and non-governmental organization research communities ensures a level of sensitivity—and cross-validation—that is effective for monitoring a CTBT. The monitoring capability is remarkably self-correcting, as was already demonstrated in response to the Kara Sea earthquake of 1997 (van der Vink, et al., 1998) and is even more the case today. Future research will further enhance this capability, for instance by expanding the fraction of the world that is fully monitored to the lowest yields.

Role of CTBT

Objectives and Limitations

The significance of a CTBT can be easily overstated, so it is important to acknowledge the limitations to such a treaty. No test-ban treaty can prevent the development of a fission bomb having a yield in the range of 15 kilotons, for example, as the gun-type weapon dropped on Hiroshima was built with sufficient confidence that nuclear-yield testing was not required.

More than half a century later, the technical knowledge for building such a weapon has to be considered widely accessible. And, with an excess of 60 tons—2,400 weapons' worth—of highly enriched uranium in civilian stockpiles around the world, the materials required to build such weapons have to be considered available, in principle (military stockpiles amount to an additional 1,840 tons or 73,600 weapons' worth of HEU)[3] (National Academy of Sciences, 2005). Indeed, South Africa had a small stockpile of gun-type weapons until it relinquished its nuclear arsenal. The detonation of such a weapon in an urban environment, whether in a military or a terrorist action, would be catastrophic.

3. The IAEA's definition of 25 kilograms of highly enriched uranium (HEU) being a "Significant Quantity" is used here to derive the equivalent number of weapons' worth of material.

Nevertheless, an objective of the CTBT is to prevent the development and deployment of far more sophisticated and devastating weapons, such as thermonuclear devices combining fission and fusion processes to release yields tens, hundreds, or even thousands of times larger. More specifically, plutonium-based implosion designs generally require nuclear-explosion testing when new (Garwin and Simonenko, 1997), and even a well-tested design may call for further testing if modifications are made, or the device is in new hands. Miniaturization so as to fit into long-range missiles, and other enhancements in military effectiveness, were among the developments of sophisticated nuclear warheads during the Cold War. These are the weapon designs that require nuclear-explosive testing, and the development and deployment of which a CTBT is intended to contain (see also NAS, 2002).

In comparison with the 10–20 kiloton yield of a gun-type fission device that would not need testing, it is clear that international capability available right now can monitor nuclear-explosion tests having much smaller yields: not only through the International Monitoring System and national technical means, but also through the complementary instrumentation of the academic, governmental (e.g., U.S. Geological Survey), and non-governmental research communities. Systems can fail and errors can be made, so it is impossible to rule out that a nuclear-explosion test might take place without being detected. However, the capability now in place makes this highly implausible, and the possibility of unrecorded (even decoupled) explosions yielding militarily useful information is therefore very limited.

Ironically, after spending hundreds of millions of dollars to deploy instruments and develop scientific capability at the cutting edge of global monitoring, the United States is currently forfeiting its role in the international effort of nuclear-test monitoring through neglect of its full annual dues to the CTBT Organization (Medalia, 2007a). This neglect jeopardizes future access to IMS data, and undermines U.S. leadership in mobilizing states party to the CTBT regime responding to a nuclear explosion should a test be conducted. After leading in so many technical aspects of monitoring capability, the United States' position is self-defeating in this regard.

Security Benefits

Still, there is a legitimate question as to whether, on balance, U.S. security does benefit from a CTBT. Several events of the past decade bear on Shalikashvili's (2001) and the NAS's (2002) conclusion that a CTBT is in the interest of U.S. security. The most recent is the North Korean nuclear-explosion test of October 2006, which clearly demonstrated the capability of both IMS and non-IMS stations in characterizing a low-yield test. The yield was so low, and well below the level announced by North Korea, that some have labeled it a failure. It was not a failure, however, in documenting North Korea's ability to detonate a nuclear device—and much is often learned from tests having lower yields than expected.

Thus there is a strong international incentive to avoid further nuclear-explosion testing by North Korea, and current diplomatic efforts appear to be accomplishing this goal. There is little doubt, however, that international pressure would be ineffective—perhaps even impossible to initiate—were any of the major nuclear powers testing at present. The current moratorium on nuclear-explosion testing is thus playing a key role in constraining the actions of North Korea in developing a militarily effective nuclear arsenal.

Similarly, the 1998 Indian testing series produced lower yields than announced, and instigated testing by Pakistan, so there remains a corresponding international incentive to avoid either nation initiating a new program of nuclear-explosion testing. As India and Pakistan have nuclear deterrents, the objective is to limit the development of weapons that are both more powerful and more readily delivered to long distances than already in these nations' stockpiles. Specifically, there is a high probability that resumption of nuclear-explosion testing by either nation would lead to renewed testing by the other, likely resulting in a spiraling arms race both in terms of sophistication and numbers of nuclear weapons deployed by India and Pakistan (and potentially triggering the resumption of testing by China).

These cases illustrate why major nuclear powers must expect to maintain a nuclear-testing moratorium for the indefinite future, if international pressure is to be sustained to dissuade all nations from undertaking nuclear-explosion testing.

Thus, the no-testing norm is effectively accepted by the global community of nations; the need for its ongoing observation means that the current moratorium is as constraining as the CTBT, but without the potential benefits of the Treaty. To be sure, a nuclear-weapon state may be driven by technical reasons to resume nuclear-explosion testing (e.g., due to a newly discovered vulnerability in its deterrent), and language currently in the CTBT allows for this eventuality, but the motivation would have to be strong in order to justify breaking the present international norm against testing.

International Norms

One may then question the need for a legally binding treaty, such as the CTBT, rather than a self-imposed moratorium as is currently in place. Indeed, some hold the view that no treaty restraining U.S. actions is in the security benefit of the United States. The NAS (2002) study addresses this issue through a review of the relative technical benefits and threats to U.S. security under distinct circumstances, such as: a) no constraints on nuclear-explosion testing; b) a voluntary moratorium on testing, as is currently in place; and c) entry into force of the CTBT.

A world with unconstrained nuclear-explosion testing advances other nations' capabilities relative to the United States', so does not serve the security interests of the U.S. Detailed analysis of the second option, a voluntary moratorium, shows that it has deficiencies in responding to nations that start testing, whether surreptitiously or openly. Those deficiencies are addressed by a CTBT, both through technical and political means; the former include an operational IMS and system of response to any nation testing, and the latter include confirmation of international norms (see below). As, on balance, the CTBT provides technical and political benefits without significantly challenging U.S. security under presently foreseeable circumstances, the Treaty is evidently in the interest of the United States (NAS, 2002).

However, the 9/11 attacks brought an additional, entirely new perspective to the question of international norms and legally binding treaties. In particular, it led to international terrorism being identified as the United States' highest security priority, and it is the potential combination of modern technology—nuclear weapons being among the most extreme examples—and radical terrorism that is acknowledged as a core threat facing the world today (Bush, 2002, 2006; National Commission on Terrorist Attacks Upon the United States, 2004).

In truth, it is exactly the civilized norms represented by international law that terrorism challenges, and 9/11 is a powerful reminder of why these norms are required. Therefore, only through a global consensus to embrace such norms can radical terrorism be effectively contained: they are necessary, though not necessarily sufficient, and the CTBT is but one example of legal norms that need strengthening. Others have made this point (e.g., Doyle, 2006), and it is more generally the case that nuclear weapons must play a different role in U.S. defense now, in the post-9/11 era, as compared with the Cold War period during which the nuclear arsenals were built up.

The current test-ban moratorium is a weak reflection of such norms, however, as it makes no formal commitment to partner nations intended to stand with the U.S. against those attacking a regime of international law. The existing moratorium—even when violated—has demonstrably played a role in constraining nuclear-explosion testing and therefore the development and deployment of new nuclear-weapon designs (so far), but the continued threats of proliferation call for a stronger system of international constraint. This stronger commitment to international norms is what the CTBT offers, and highlights not only the U.S. interest in ratification but—once ratified—in taking the lead in bringing about the treaty's entry into force.

Periodic Review and Laboratory Privatization

Recent developments thus reinforce the conclusion that a CTBT is in the interest of U.S. security, even more than could be appreciated before 9/11. Still, the future is uncertain, and a CTBT might be less effective—or allow new vulnerabilities—under circumstances that may emerge over the coming years or decades. Therefore, as part of a decision to support its entry into force, it would be prudent for the United States to establish an internal process for reviewing the CTBT's role in national and international security. This would be complementary to the international review process specified in Article VIII of the Treaty, and would enhance the utility of the safeguards associated with U.S. implementation of the Treaty.

Indeed, Shalikashvili (2001) recommended that the administration and Senate should jointly review the CTBT regime once per decade after ratification. Doing so would provide a periodic check that the Treaty continues to serve the nation's security interests, with due consideration of the United States' nuclear-weapons policy and posture as these evolve. Technical questions about sustaining U.S. defense capability, as well as the ability to verify the CTBT, would be among the central topics of such a review. More than enough capability exists, in the national laboratories and elsewhere, for periodic review of the CTBT regime.

As with annual assessments of the stockpile, developing a trustworthy process would be central to establishing the credibility of such a review. In this regard, matters have changed somewhat in the past few years. At the time of the 1999 Senate debate, for instance, the national laboratories could be viewed as public institutions providing independent technical information to advise a wider political dialogue.

In particular, Los Alamos and Lawrence Livermore National Laboratories were managed by the University of California (UC), a non-profit public institution with a reputation for fostering openness and free expression. The laboratory directors, testifying in the Senate, no doubt weighed the potential impact of a CTBT on their organizations' future, but they were not constrained from presenting a technically reliable, balanced and complete analysis.

The present situation is different, however, as the nuclear design laboratories are now managed by limited-liability companies (LLCs) in which UC partners with private, for-profit entities. These young LLCs have not yet had the opportunity to establish a record for fostering free expression, so their credibility could be viewed as yet-to-be fully established. Therefore, although the laboratories have the requisite technical expertise to inform a debate about CTBT, they may not—on their own—be in a position to communicate that information as effectively as was previously the case.

This is a recent development, suggesting the need for a new mechanism if the overall security—technical, military, foreign relations—basis of the CTBT regime is to be perceived as objectively reviewed within the U.S. The national laboratories' technical expertise must be an important component of such a review. As successfully demonstrated by the annual assessment of the nuclear-weapons stockpile, however, an independent and broader entity that is competent at the task can be made responsible for leading the review itself.

Conclusion

Results of the past decade strongly reinforce the conclusions that the CTBT i) does not undermine the United States' ability to sustain an effective nuclear deterrent; ii) can be monitored with a sensitivity more than adequate for effective verification; and iii) does enhance U.S. security by constraining development and deployment of the most devastating weapons currently known. It serves to reinforce international norms that are all the more important at a time when radical terrorism has become the leading security priority of the U.S..

In the past, many of the major treaties bearing on nuclear weapons—INF, SALT, START, and SORT—have been bilateral rather than global in extent; neither SALT, START, nor SORT (or LTBT and TTBT) attempted a zero-level threshold, as does CTBT. In this sense, the Comprehensive Test-Ban Treaty exemplifies the global-verification regime envisaged by President Ronald Reagan for controlling nuclear weapons worldwide.

To be sure, significant nuclear arms control and disarmament efforts date back to the Baruch-Lilienthal Plan (1946) and the Eisenhower administration, and led to the Nuclear Non-Proliferation Treaty (NPT) and IAEA regime presently in force. An end to nuclear-explosion testing is cited in the Preamble of the NPT, and establishing an effective CTBT is one of the key objectives identified at the 1995 Review Conference extending the NPT for an indefinite duration. The CTBT is thus viewed by most of the world, including the nuclear-weapons states, as being intimately connected with nuclear non-proliferation (e.g., Medalia, 2007a; Jonas, 2007).

Based on the findings reviewed here, several actions have been identified for enhancing the CTBT regime and U.S. security, as summarized in Table 3. Though technically feasible on the timescales indicated, it is clear that these recommendations involve significant political issues that must also be addressed (e.g., Gallagher, 1999; Medalia, 2007a). For example, both Congressional and presidential election cycles will plausibly influence the pace as well as the content of a debate toward CTBT ratification. And, although the technical information is readily available, its political consequences may likely take time to work out. Similarly, establishing a nuclear-weapons policy and posture will be an important task for the new administration that takes power in 2009.

These considerations suggest that one to two years may have to be added to the schedule identified for the Intermediate-Term actions

Table 3 Technically Feasible Actions Enhancing Security

Near Term (6–12 months)

Reinstate full assessed U.S. funding for CTBT Organization*

Publish descriptions of U.S. sub-critical-experiment monitoring in scientific literature

Begin background discussions of CTBT in the U.S. Senate, including specific steps to build support for ratification and entry into force

Intermediate Term (1–2 years)

Establish post-9/11 U.S. nuclear-weapons policy and posture

Enhance coordination between the international verification regime, which includes the IMS, and other (academic-research, NGO) monitoring efforts

Debate CTBT, leading to ratification
(e.g., establish internal periodic review mechanisms, as necessary)

Long Term (5–10 years)

Review and enhance CTBT regime
- Utility in controlling proliferation
- Ability to monitor
- Ability to sustain U.S. security needs

*The current implementation of the CTBTO—until the CTBT enters into force—is the CTBT Organization Preparatory Commission.

in Table 3 to allow for the political activities that will necessarily be required. Still, developments both within the U.S. as well as internationally, including the opportunities and challenges of the upcoming 2010 NPT Review Conference, indicate the need for timely action on the CTBT.

The first concern about U.S. Senate ratification of the CTBT was that there had been inadequate time for the policy debate in 1999 (Table 1). There is no excuse for that continuing to be the case. The United States should start an informed discussion of the Comprehensive Nuclear Test Ban Treaty without delay.

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ACRONYMS

CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO	CTBT Organization or, as currently, its Preparatory Commission
DARHT	Dual-Axis Radiographic Hydrodynamic Test Facility
GPS	Global Positioning System
HEU	Highly Enriched Uranium
IAEA	International Atomic Energy Agency
IMS	International Monitoring System
INF	Intermediate Forces Treaty
LEP	Life Extension Program
LLC	Limited Liability Company
LTBT	Limited Test Ban Treaty
NAS	National Academy of Sciences
NGO	Non-Governmental organization
NIF	National Ignition Facility
NPT	Nuclear Non-Proliferation Treaty
SALT	Strategic Arms Limitation Treaties
SORT	Strategic Offensive Reduction Treaty
START	Strategic Arms Reduction Treaties
TTBT	Threshold Test Ban Treaty
UC	University of California

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