The Comprehensive Nuclear Test Ban Treaty: Technical Issues for the United States

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THE COMPREHENSIVE NUCLEAR TEST BAN TREATY—TECHNICAL ISSUES FOR THE UNITED STATES

Committee on Reviewing and Updating Technical Issues Related to the
Comprehensive Nuclear Test Ban Treaty

Policy and Global Affairs

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PREFACE

The Office of the Vice President and the White House Office of Science and Technology Policy requested this study, which was carried out under contracts with the Department of State and Department of Energy, with additional support from the Carnegie Corporation of New York and the National Academy of Sciences. The committee formed by the National Research Council (NRC) to carry out the study has conducted a review and assessment of changes in technical issues that have occurred since the NRC's previous report on this topic, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty* (NRC, 2002). In particular the committee was asked to address the following:

1) The risks in ensuring, over the longer term, a safe and reliable nuclear weapons stockpile absent underground nuclear-explosion testing, particularly including the experience of the U.S. stockpile stewardship program. (See Chapter 1)
2) The status of nuclear-explosion detection, taking into account the operating experience of the international monitoring system and improvements in U.S. national technical means in the last decade. (See Chapter 2)
3) The commitments required to sustain the U.S. stockpile and effective nuclear explosion monitoring. (See Chapter 3)
4) The potential technical advances to nuclear-weapon capabilities that might be gained by other countries from testing that might escape detection compared with those advances available with a return to full-yield testing in a non-test-ban environment. (See Chapter 4)

In addition, some further emphasis on certain issues was provided to the committee at its first meeting by Under Secretary of State for Arms Control and International Security, Ellen Tauscher, and Under Secretary of Energy for Nuclear Security and National Nuclear Security Administration Administrator, Thomas D'Agostino. They requested that the committee include its views in the study on (1) research that could improve or address shortfalls in monitoring capabilities, (2) the 2008 Comprehensive Nuclear-Test-Ban-Treaty Organization (CTBTO) Integrated Field Exercise and the utility of on-site inspections as a verification tool, (3) lessons learned from the 2006 and 2009 DPRK nuclear explosions, and (4) the possible effects of undetectable cheating. Items 1-3 are discussed in Chapter 2, and item 4 is discussed in Chapter 4.

In the course of this study, the committee has benefited from the invaluable assistance of many dedicated experts in different aspects of these issues, including representatives of U.S. government agencies and the Preparatory Commission of the CTBTO. Those who spoke to the committee at its meetings are listed in Appendix B. The committee was also granted access to the 2010 CTBT National Intelligence Estimate (NIE) and other intelligence reports relevant to the issues it was asked to address.

The Subcommittee on Seismology (see the biographies of members in Appendix A) was separately constituted for the purpose of providing input to the parent committee. At the direction of the committee, the subcommittee produced written input on seismology issues identified by the committee and interacted with the committee as needed. The subcommittee also raised issues to the committee that in its view had a material bearing on the committee's work. In cooperation with subcommittee members, the committee integrated the subcommittee's material into the committee's report and worked with the subcommittee to produce technical appendices to further explain certain issues related to the report. We would especially like to thank subcommittee member William Walter of Lawrence Livermore National Laboratory for his extraordinary work to see the study to completion.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its 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 review comments and draft manuscript remain confidential to protect the integrity of the process.

We wish to thank the following individuals for their review of this report: John Ahearne, Sigma Xi, The Scientific Research Society; Mona Dreicer, Lawrence Livermore National Laboratory; John Foster, Northrop Grumman Aerospace Systems; Ward Hawkins, Los Alamos National Laboratory; Stephen LaMont, Los Alamos National Laboratory; Cherry Murray, Harvard University; C. Paul Robinson, Sandia National Laboratories; Lawrence Welch, Institute for Defense Analyses; and Jay Zucca, Lawrence Livermore National Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Richard Meserve and Russell Hemley, both from the Carnegie Institution for Science. Appointed by the National Academies, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the Academy.

In the following chapters, we review the technical changes related to the U.S. nuclear stockpile and to nuclear-explosion test monitoring that have occurred in the past ten years and place these in the context of their significance for national security. The discussion covers maintaining a safe, secure, and reliable nuclear stockpile; maintaining and expanding the ability to place clandestine testers at risk of detection via an effective monitoring capability; sustaining the U.S. human and physical infrastructure of these capabilities; and assessing the risks of undetected clandestine testing in contrast to the risks of full-yield nuclear-explosion testing unhindered by international agreements. To the extent that weapons laboratory management and contracting issues impinge on the quality of the nuclear weapons workforce and the sustainability of critical technical capabilities, the committee has commented on these issues.

The committee prepared both a classified and an unclassified version of this report. The National Research Council completed its peer review of the reports in March 2011 and then turned over the reports to the sponsoring agencies for security review. The committee updated data in the reports during the security review, but some text and figures reflect the March 2011 date the reports were sent to the agencies. The findings and recommendations are identical in the two versions, except for a few cases in which classified passages are paraphrased in the unclassified report.

For the benefit of the reader, a glossary of specialized terms from the 2010 CTBT NIE is provided as Appendix K.

Ellen D. Williams
Chair

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EXECUTIVE SUMMARY

This report is a review and update of the 2002 National Research Council report, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty (CTBT)* (hereafter the *2002 Report*). The committee was asked to assess:

- plans to maintain the safety and reliability of the U.S. nuclear stockpile without nuclear-explosion testing;
- the U.S. capability to detect, locate, and identify nuclear explosions;
- commitments necessary to sustain the stockpile and the U.S. and international monitoring systems; and
- potential technical advances countries could achieve through evasive testing and unconstrained testing.

Provided that sufficient resources and a national commitment to stockpile stewardship are in place, the committee judges that the United States has the technical capabilities to maintain a safe, secure, and reliable stockpile of nuclear weapons into the foreseeable future without nuclear-explosion testing. The Administration, in concert with Congress, should formulate and implement a comprehensive plan that provides a clear vision and strategy for maintaining the nation's nuclear deterrence capabilities and competencies, as recommended in the 2010 Nuclear Posture Review and related studies. Sustaining these technical capabilities will require action by the National Nuclear Security Administration (NNSA), with the support of others, on at least the following elements:

- a strong scientific and engineering base maintained through a continuing dynamic of experiments linked with analysis;
- a vigorous surveillance program;
- adequate ratio of performance margins to uncertainties;
- modernized production facilities; and
- a competent and capable workforce with a broad base of nuclear security expertise.

The United States has technical capabilities to monitor nuclear explosions in four environments—underground, underwater, in the atmosphere and in space. Technical capabilities have improved significantly in the past decade, although some operational capabilities are at risk. Seismology, the most effective approach for monitoring underground nuclear-explosion testing (the environment in which all known nuclear-explosion tests have been conducted since 1980), now provides much more sensitive detection, identification, and location of explosions. Most of the seismic stations of the International Monitoring System (IMS) under the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) are operating now, and the 90 percent confidence levels for IMS seismic detection are well below 1 kiloton (kt) worldwide for fully coupled explosions. With the inclusion of regional monitoring and improved understanding of backgrounds, an evasive tester in Asia, Europe, North Africa, or North America would need to restrict device yield to levels below 1 kt (even if the explosion were fully decoupled) to ensure no more than a 10 percent probability of detection by the IMS.

The United States' global monitoring capabilities, or national technical means (NTM), provide monitoring capability that is superior to that of the IMS and can focus on monitoring countries of concern to the United States. However, the IMS provides valuable data to the United States, both as an augmentation to the U.S. NTM and as a common baseline for international assessment and discussion of potential violations when the United States does not wish to share NTM data. Thus, the United States should support both the completion of the IMS and its operations, training and maintenance, whether or not the Comprehensive Nuclear Test Ban Treaty (CTBT) enters into force.

Constraints placed on nuclear-explosion testing by the monitoring capabilities of the IMS, and the better capabilities of the U.S. NTM, will reduce the likelihood of successful clandestine nuclear-explosion testing, and inhibit the development of new types of strategic nuclear weapons. The development of weapons with lower capabilities, such as those that might pose a local or regional threat, or that might be used in local battlefield scenarios, is possible with or without the CTBT for countries of different levels of nuclear sophistication. However, such developments would not require the United States to return to testing in order to respond because it already has—or could produce—weapons of equal or greater capability based on its own nuclear-explosion test history. Thus, while such threats are of great concern, the United States would be able to respond to them as effectively whether or not the CTBT were in force.

A technical need for a return to nuclear-explosion testing would be most plausible if the United States were to determine that adversarial nuclear activities required the development of weapon types not previously tested. In such a situation, the United States could invoke the supreme national interest clause and withdraw from the CTBT.

As long as the United States sustains its technical competency, and actively engages its nuclear scientists and other expert analysts in monitoring, assessing, and projecting possible adversarial activities, it will retain effective protection against technical surprises. This conclusion holds whether or not the United States accepts the formal constraints of the CTBT.

SUMMARY

This committee was asked to review and update the 2002 National Research Council (NRC) report, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty* (NRC, 2002; hereafter referred to as the *2002 Report*). That report documented the status of technical issues at the time the Senate declined its advice and consent to ratification of the Comprehensive Nuclear Test Ban Treaty (CTBT) in 1999. The statement of task for the current report requests the committee's assessment of the following four areas, drawing on the latest evidence:

1) *Maintaining the safety and reliability of the U.S. stockpile*. The committee will assess, (along with other sources of information) information developed for and produced by the Nuclear Posture Review, the Administration's plan to manage the risks in ensuring, over the longer term, a safe and reliable nuclear weapons stockpile absent underground nuclear-explosion testing. The experience of the U.S. stockpile stewardship program, particularly in the last decade, will also be taken into account.[1] (See Chapter 1)
2) *Nuclear explosion detection, location, and identification.* The committee will assess present nuclear explosion detection capabilities, taking into account the totality of assets accessible to the United States, including (a) any improvements in U.S. national technical means in the last decade and (b) operating experience of the international monitoring system. The committee might also consider how these capabilities are expected to improve over time. (See Chapter 2)
3) *Sustainability.* The committee will assess what commitments are required to sustain (a) America's nuclear stockpile; (b) the U.S. monitoring system; and (c) an adequate international verification regime, including on-site inspection. (See Chapter 3)
4) *Technical advances.* The committee will assess the potential technical advances to nuclear weapon capabilities for other countries (a) that result from evasive and non-evasive testing at levels below the U.S. detection capability and (b) that result from returning to full-yield testing in a non-test-ban environment. (See Chapter 4)

Maintaining and sustaining U.S. capabilities under the CTBT depends on both political and technical components. This report focuses on technical issues. A clear understanding of what can and cannot be achieved technically is important for informing the policy question of whether the ratification and entry into force (EIF) of the CTBT is in the national interest of the United States. The committee's findings and recommendations in each of the four topic areas in the statement of task are identified throughout the text and a complete list is given in Chapter 5. Because some of the findings and recommendations relate to specific programs or topics, only a selected subset that is judged to be of interest to the broader community is brought forward into this Summary. However, the numbering of the findings and recommendations as they appear in the text is preserved here, to facilitate the location of the corresponding discussion in the chapters.

SAFETY, SECURITY, AND RELIABILITY OF THE U.S. NUCLEAR WEAPONS STOCKPILE

At the time of the *2002 Report*, the Stockpile Stewardship Program (SSP) was in its early stages, and there was uncertainty about maintaining the stockpile in the absence of

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[1] The committee included safety, security, and reliability in its study of issues.

nuclear-explosion testing. The intervening 10 years have seen the SSP discover and resolve significant stockpile issues, but notable concerns have also arisen about maintaining the physical and human infrastructure needed for the SSP.

Finding 1-1: The technical capabilities for maintaining the U.S. stockpile absent nuclear-explosion testing are better now than anticipated by the *2002 Report*.

Finding 1-2: Future assessments of aging effects and other issues will require quantities and types of data that have not been provided by the surveillance program in recent years.

Finding 1-3: The committee judges that Life-Extension Programs (LEPs) have been, and continue to be, satisfactorily carried out to extend the lifetime of existing warheads without the need for nuclear-explosion tests. In addition to the original LEP approach of *refurbishment*, sufficient technical progress has been made since the *2002 Report* that *re-use* or *replacement* of nuclear components can be considered as options for improving safety and security of the warheads.

Finding 1-4: Provided that sufficient resources and a national commitment to stockpile stewardship are in place, the committee judges that the United States has the technical capabilities to maintain a safe, secure, and reliable stockpile of nuclear weapons into the foreseeable future without nuclear-explosion testing. Sustaining these technical capabilities will require at least the following:

- *A Strong Scientific and Engineering Base*. There must be continued adherence to the principle that the ability to assess and certify weapons rests on technical understanding of weapons phenomena, data from past nuclear-explosion tests, computations, and data from past and ongoing experiments. Maintaining both a strategic computing capability and modern non-nuclear-explosion testing facilities (for hydrodynamic testing, radiography, material equation-of-state measurements, high explosives testing, and fusion testing) is essential for this purpose.
- *A Vigorous Surveillance Program*. An intensive surveillance program aimed at discovering warhead problems is crucial to the health of the stockpile.
- *Adequate Ratio of Margin to Uncertainty.* Performance margins that are sufficiently high, relative to uncertainties, are key ingredients of confidence in weapons performance.
- *Modernized Production Facilities.* Most of the nuclear weapons production facilities are old (50 years in some cases) and are both difficult and costly to operate in accordance with modern standards of safety and security.
- *A Competent and Capable Workforce.* Nuclear weapons work (e.g., the SSP) is key to meeting a range of challenges in the broader national security landscape. Exploration of these broader areas (nonproliferation programs, render safe, etc.) can provide opportunities for intellectual stimulation and professional development that will attract a diverse, capable workforce. It is equally important to ensure that the Department of Defense, particularly the Defense Threat Reduction Agency, the Navy's Strategic Systems Project Office, and the Air Force's Ballistic Missile Organization, maintain a technically competent workforce.

Recommendation 1-1: To address each of the essential elements of stockpile stewardship listed in Finding 1-4, NNSA, working with the Administration and Congress as appropriate, should:

- *Maintain a continuing dynamic of experiments linked with analysis.* Both are essential to maintaining the capability to render judgments about stockpile issues.
- *Maintain a vigorous surveillance program* that is systematic; is statistically based where possible; and continuously reflects lessons learned from annual surveillance, LEPs, fixing problems, and science-based analysis. Nondestructive tools and experimentally validated computational analysis should be developed and applied to introduce more predictive capability into the surveillance system.
- *As part of each LEP, explore options for achieving adequate margins* through reuse or replacement scenarios in addition to refurbishment, to determine how best to meet military, technical, and policy objectives. Assess uncertainties associated with each scenario.
- *Develop and implement a long-term production facility modernization plan.* This should include maintaining a plutonium science and production facility, including the ability to produce various types of pits for weapons in the stockpile.
- *Broaden the base of its nuclear expertise by involving nuclear-capable personnel in related national security projects* (nuclear forensics, intelligence, threat reduction programs, basic science applications of stewardship activities, etc.).

TECHNICAL MONITORING CAPABILITIES AND CHALLENGES

The possibility of nuclear-explosion testing must be considered in four environments–underground, underwater, in the atmosphere, and in space. Each of the four environments requires different monitoring methods, each with different capabilities. Three streams of data for nuclear-explosion test monitoring are available: national technical means (NTM),[2] the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO),[3] and complementary sources (e.g., the scientific research community). NTM give the United States significant additional information beyond what is available to other countries that do not have a robust NTM program. U.S. NTM can focus on monitoring countries of concern to the United States. The U.S. global monitoring capabilities are generally better than those of the CTBTO because they can enhance data available to the CTBTO with classified capabilities. However, the inclusion of classified means and data limits the extent to which analyses and even results may be shared and used openly.

Finding 2-1: U.S. National Technical Means provide monitoring capability that is superior to that of the CTBTO, but the use of U.S. NTM for diplomatic purposes may be constrained due to its largely classified nature.

Finding 2-2: The International Monitoring System provides valuable data to the United States, both as an augmentation to the U.S. NTM and as a common baseline for international assessment and discussion of potential violations when the United States does not wish to share NTM data.

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[2] In the United States, the responsibility for monitoring nuclear-explosion tests rests with the Air Force, which supports NTM for detection, location and identification through the U.S. Atomic Energy Detection System (USAEDS).

[3] Under the CTBT, the international monitoring effort consists of the IMS, which generates data from its radionuclide, seismic, infrasound, and hydroacoustic networks; the International Data Centre, which collects and processes the IMS data; and a secure communications system, all managed by the CTBTO. The identification and attribution of detected signals is not carried out by the CTBTO but is the responsibility of the member states to the treaty. Throughout the text, the acronym *CTBTO* refers to the Preparatory Commission of the Comprehensive Nuclear Test Ban Treaty.

Recommendation 2-1: The United States should support both the completion of the IMS and its operations, training, and maintenance, whether or not the CTBT enters into force. If the CTBT were to enter into force, the resulting expertise would also aid in gaining consensus on compliance issues, including, for example, authorizing an on-site inspection.

Seismic Monitoring[4]

Seismology is the most effective technology for monitoring underground nuclear-explosion testing. Seismic monitoring for nuclear explosions is complicated by the great variety of geologic media and the variety and number of earthquakes, chemical explosions, and other non-nuclear phenomena generating seismic signals every day.

Finding 2-4: Technical capabilities for seismic monitoring have improved substantially in the past decade, allowing much more sensitive detection, identification, and location of nuclear events. More work is needed to better quantify regional monitoring identification thresholds[5], particularly in regions where seismic waves are strongly attenuated.

Recommendation 2-3: To meet its national security needs, the United States should continue to enhance and sustain its NTM seismic monitoring capabilities.

Finding 2-5: One of the major advances in monitoring in the last 10 years is that most of the IMS seismic stations are operating now, and most of those have been certified for data quality (including calibration) and integrity (with respect to tampering and data authenticity). The threshold levels for IMS seismic detection are now well below 1 kt worldwide for fully coupled explosions. (See Chapters 2 and 4 for further discussion)

Finding 2-6: Seismic technologies for nuclear monitoring have the potential to improve event detection, location, and identification substantially over the next years to decades.

Recommendation 2-4: The United States should renew and sustain investment in seismic R&D efforts to reap the rewards of new methodologies, source models, Earth models, and data streams to enhance underground nuclear explosion monitoring, regardless of the status of CTBT ratification.

Radionuclide Monitoring

Nuclear explosions produce radionuclides from fission and from nuclear reactions in the materials in and around the device. Such radionuclides are produced in large quantities and high concentrations relative to natural processes and can be detected when they are either released (or vented) into the atmosphere or deposited on the ground near the detonation point.

Finding 2-8: AFTAC has demonstrated notable achievements over the past decade, including major enhancements in all aspects of radionuclide monitoring.

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[4] In this report, the committee uses the term *monitoring* to refer to all aspects of detection and characterization of an event (e.g., nuclear vs. non-nuclear, geolocation, and yield estimates).

[5] Throughout this report (unless otherwise qualified), by “detection threshold” the committee means detection at 90 percent confidence and at enough stations to provide a location estimate.

Recommendation 2-5: The United States should continue to actively support radionuclide collection, including R&D activities to better discriminate nuclear-test signature radionuclides from background, thus improving the ability to detect well-contained and lower-yield nuclear-explosion tests.

Finding 2-9: In the past 10 years, the IMS radionuclide network has gone from being essentially non-existent to a nearly fully functional and robust network with new technology that has surpassed most expectations.

Finding 2-11: Ongoing measurement and understanding of global backgrounds of radionuclides relevant to nuclear-explosion monitoring are critical for improving radionuclide detection.

Hydroacoustic Monitoring

Hydroacoustic monitoring for nuclear explosions in or near bodies of water has been utilized by the United States for many decades.

Finding 2-13: The IMS detection threshold for in-water explosions is 10 tons (0.01 kt) or below worldwide and below 1 ton (<0.001 kt) throughout the majority of the world's oceans.

Infrasound Monitoring

Infrasound waves are sound waves with frequencies between 0.01 and 10 Hz, below the sensitivity range of the human ear. They are produced by explosions in the atmosphere and can be detected at great distances. They are also produced by ground motion from underground explosions, and provide a complementary source of data to detect and discriminate underground nuclear-explosion tests.

Finding 2-16: Integration of infrasound with seismic data and analysis will provide better detection, location, and identification of explosions.

Satellite-Based Monitoring

The United States has produced and maintained an impressive satellite nuclear detonation detection capability for continuous coverage of Earth and space. Modern coverage is provided by nuclear detonation detection payloads carried on multi-mission satellites (Global Positioning System, [GPS] and, at geosynchronous altitudes, the Defense Support Program [DSP] satellites), which are procured and operated by the U.S. Air Force.

A decade ago when the *2002 Report* was written it was anticipated that there would continue to be an effective satellite nuclear detonation detection capability with improvements timed to coincide with Air Force plans to modernize GPS and DSP.

There is currently uncertainty about whether the requirement for nuclear detection is still a sufficiently high priority relative to other military requirements (See Chapter 2 and Appendix G for further discussion).

Finding 2-17: Sustainment of the U.S. satellite monitoring capability to detect any nuclear explosion in the atmosphere or space, whatever its origin, will continue to be in the

interest of the United States and its allies, regardless of whether the CTBT enters into force.

Recommendation 2-8: Enhanced satellite nuclear detonation detection systems should be deployed in upgrades to GPS (GPS Block IIF and Block III) and the follow-on to DSP, the Space-Based Infrared System (SBIRS). Provision for adequate ground-based data processing is also essential. Decisions regarding whether and at what level to maintain the satellite nuclear detonation detection capability should be made as part of high-level national security policy and acquisition assessments.

On-Site Inspection

Under the CTBT after entry into force, each State Party has the right to request an on-site inspection (OSI) to determine whether a nuclear explosion has been carried out in violation of the treaty and to gather any facts that might assist in identifying any possible violator. Inspection requests must be based on data collected by the IMS, NTM, or both. The OSI request must be approved by the CTBTO Executive Council.

Finding 2-22: A CTBTO on-site inspection (OSI) would have a high likelihood of detecting evidence of a nuclear explosion with yield greater than about 0.1 kilotons, provided that the event could be located with sufficient precision in advance and that the OSI was conducted without hindrance.

SUSTAINING U.S. TECHNICAL CAPABILITIES UNDER THE CTBT

Two technical programs that are essential to maintaining U.S. technical capabilities under the CTBT are the U.S. nuclear weapons program, including both DOE/NNSA and DOD components, and the U.S. monitoring and verification program. Chapters 1 and 2 of this report discuss these programs, and Chapter 3 discusses challenges to sustaining them.

Sustaining the U.S. Nuclear Weapons Program

Finding 3-2: A strong national commitment to recruiting and sustaining a high-quality workforce; recapitalizing aging infrastructure and force structure; and strengthening the science, engineering, and technology base is essential to sustaining a safe, secure, and reliable stockpile, as well as necessary explosion-monitoring capability for the United States.

Recommendation 3-1: The Administration, in concert with Congress, should formulate and implement a comprehensive plan that provides a clear vision and strategy for maintaining the nation's nuclear deterrence capabilities and competencies, as recommended in the 2010 Nuclear Posture Review and related studies.

Recommendation 3-2: The DOE/NNSA should re-evaluate the current contract system for carrying out the tasks of the nuclear weapons program. At a minimum, any new approach should:

- **Reduce the number of requirements in directives and simultaneously transform those requirements to performance goals (prescribing what must be done, not how to do it).**

- **Shift the balance of incentives in contracts for the weapons laboratories to emphasize successful implementation of the technical mission.**

Sustaining the U.S. Monitoring and Verification Program

Finding 3-6: Continued enhancement of the USAEDS is necessary to monitor the CTBT. Research and development of advanced monitoring capabilities are needed, including research and training at universities of the next generation of scientists and engineers.

Recommendation 3-5: A sustained, predictable program of investment in nuclear-explosion monitoring R&D should be coordinated among the responsible U.S. agencies. This program should specifically include investments in university research and training programs focused on technical disciplines critical for treaty monitoring.

Finding 3-10: The OSI capability of the CTBTO lags behind the readiness of the IMS; however, steps have been taken, such as the 2008 Integrated Field Exercise, which have improved OSI capabilities significantly.

Recommendation 3-9: The United States should support the CTBTO OSI work by participating fully in all of its aspects, including training and field exercises.

CTBT Safeguards

Six CTBT safeguards were proposed in 1995. These safeguards make no mention of nuclear weapon production capabilities. There is also no mention of a means to assess whether the safeguards are adequately implemented.

Finding 3-11: Without agile production capabilities, it is not possible to promptly correct deficiencies revealed by surveillance or to remanufacture components or weapons when required.

Recommendation 3-10: The U.S. CTBT safeguards should include the maintenance of adequate production and non-nuclear-explosion testing facilities.

Finding 3-12: There is currently no mechanism that would enable Congress to assess whether the U.S. CTBT safeguards were being fulfilled after entry into force.

Recommendation 3-11: Under the CTBT, the Administration should prepare an annual evaluation of the ongoing effectiveness of safeguards and formally transmit it to Congress.

POTENTIAL TECHNICAL ADVANCES FROM NUCLEAR-EXPLOSION TESTING

A critical technical issue is whether the risk of adversaries developing new or improved nuclear weapons capabilities is greater with a CTBT or without the CTBT.

Finding 4-1: The Nuclear Weapon States have been able to maintain their nuclear weapons programs under a nuclear-explosion-test moratorium and are likely to be able to make nuclear weapons modifications that fall within the design range of their test experience without resorting to nuclear-explosion testing.

Hydronuclear Testing

The term *hydronuclear* refers to a test in which criticality is achieved but the nuclear yield is less than the energy released by the high explosive. In this report the committee distinguishes hydronuclear tests as a subset of nuclear-explosion tests, most of which have nuclear yield far greater than the energy released by the high explosive but all of which are banned under the CTBT.

Finding 4-2: Hydronuclear tests would be of limited value in maintaining the United States nuclear weapon stockpile in comparison with the advanced tools of the Stockpile Stewardship Program.

Finding 4-3: Based on Russia's extensive history of hydronuclear testing, such tests could be of some benefit to Russia in maintaining or modernizing its nuclear stockpile. However, it is unlikely that hydronuclear tests would enable Russia to develop new strategic capabilities outside of its nuclear-explosion test experience.

Given China's apparent lack of experience with hydronuclear testing, it is not clear how China might utilize such testing in its strategic modernization.

Evasive Nuclear-Explosion Testing

Finding 4-4: An evader determined to avoid detection would test at levels the evader believes would have a low probability of detection.

Finding 4-5: Mine masking is a less credible evasion scenario than it was at the time of the *2002 Report* because of improvements in monitoring capabilities.

Finding 4-6: With the inclusion of regional monitoring, improved understanding of backgrounds, and proper calibration of stations, an evasive tester in Asia, Europe, North Africa, or North America would need to restrict device yield to levels below 1 kiloton (even if the explosion were fully decoupled) to ensure no more than a 10 percent probability of detection for IMS and open monitoring networks.

Finding 4-7: For IMS and open monitoring networks, methods of evasion based on decoupling and mine masking are credible only for device yields below a few kilotons worldwide and at most a few hundred tons at well-monitored locations.

Finding 4-8: The States most capable of carrying out evasive nuclear-explosion testing successfully are Russia and China. Countries with less nuclear-explosion testing experience would face serious costs, practical difficulties in implementation, and uncertainties in how effectively a test could be concealed. In any case, such testing is unlikely to require the United States to return to nuclear-explosion testing.

Finding 4-9: Better technical understanding of the decoupling process in various types of geologies would likely improve the capability to detect evasive nuclear-explosion testing.

Recommendation 4-1: If the possibility of evasive nuclear-explosion testing through cavity decoupling continues to be a concern, the United States should:

- **Apply modern computational and experimental methods to understand the decoupling process in various geologies;**
- **Identify areas such as geologic salt domes advantageous for decoupling and consider the need for additional monitoring; and**
- **Identify indicators that a country is using—or may be planning to use—decoupling as an evasion strategy.**

Technical Advances

Finding 4-10: Threats could arise by clandestine nuclear weapons activity. For instance, a country with no testing experience and a modest industrial base could confidently build and deploy a single-stage, unboosted nuclear weapon without any testing, if it had access to sufficient quantities of fissile material. These advances could be made whether or not the CTBT were in force. However, it is highly likely that the United States could counter these threats without returning to nuclear-explosion testing and thus could respond equally well whether or not the CTBT were in force.

Finding 4-11: The value of low-yield evasive underground testing to a particular country depends on that country's nuclear-explosion test experience and/or design sophistication.

- **Nuclear Weapon States could use low-yield evasive testing to partially validate design codes and modernize their arsenals.**
- **Countries with lesser test experience could build confidence with weapons physics experiments or develop and certify inefficient, unboosted fission weapons that might pose a regional threat.**

Because such tests may be undetectable, these advances could be made whether or not the CTBT were in force.

Finding 4-12: Russia and China are unlikely to be able to deploy new types of strategic nuclear weapons that fall outside of the design range of their nuclear-explosion test experience without several multi-kiloton tests to build confidence in their performance. Such multi-kiloton tests would likely be detectable (even with evasion measures) by appropriately resourced U.S. national technical means and a completed IMS network.

Finding 4-13: Other States intent on acquiring and deploying modern, two-stage thermonuclear weapons would not be able to have confidence in their performance without multi-kiloton testing. Such tests would likely be detectable (even with evasion measures) by appropriately resourced U.S. national technical means and a completed IMS network.

CONCLUSIONS

First, although there are legitimate concerns about maintaining the capabilities needed to sustain U.S national security into the future, the results of this committee's deliberations have shown that these concerns are *not* the result of intrinsic technical limitations and are *not* limited by a possible future under the CTBT. Indeed, this committee has found that the SSP has been more successful than was anticipated in 1999. Similarly, the status of U.S national monitoring and the International Monitoring System has improved to levels better than predicted in 1999.

As a result, the committee concludes that the United States is now better able to maintain a safe and effective nuclear stockpile and to monitor clandestine nuclear-explosion testing than at any time in the past. This result has been achieved because the technical infrastructure that was developed during the Cold War has been sustained by the technical workforce trained at that time and by the successors that they have in turn nurtured.

In investigating many of the concerns that were presented to this committee, the committee found that the majority reflected real or perceived inadequacy of support for this human (and the related physical) infrastructure. The committee noted in the report a number of specific examples of technical capabilities that are under pressure due to competing priorities. The committee did not attempt to judge the balance of priorities reflected, or the funding levels that might be needed to address any specific instance. Instead, the committee emphasizes that the decay of capabilities under resource stress has consequences equivalent to those of a direct policy decision. The most serious requirement for sustaining the U.S. stockpile and monitoring capabilities is a clear statement of policy regarding the capabilities that must be maintained, combined with management and support focused on achieving well-defined technical goals underpinning those capabilities. The need for such action arises whether or not the United States ratifies the CTBT.

Second, the technical assessment of risks to national security that might arise as a result of the United States ratifying the CTBT must be addressed on an objective basis. Because of the results of the SSP, those risks are limited. The SSP has captured knowledge of the United States history of nuclear-explosion tests and systematized it into a discipline that could be used to recreate any of the previously tested competencies. As a result, the CTBT would not prevent the United States from responding effectively if military and political decisions required development of previously tested weapon types not now present in the stockpile. A technical need for a return to testing would be most plausible if the United States were to determine that adversarial nuclear activities required the United States to develop weapons that could not be confidently certified based on its nuclear-explosion testing experience. In such a situation, the United States could invoke the supreme national interest clause and withdraw from the CTBT.[6]

Third, surprise by clandestine nuclear weapons activity cannot be prevented with absolute certainty with or without the CTBT, but a fully functioning CTBTO after entry into force—with completion and sustainment of the IMS and a strengthened OSI capability—can help reduce that risk. The appropriate technical questions for this point are (1) What types of threats could arise without the United States having ample forewarning via its nuclear-test-monitoring capabilities? and (2) Would a return to testing ameliorate those threats?

There are threats that could arise without detection, with or without the CTBT. For instance, a single-stage, unboosted nuclear weapon can be confidently built and deployed without nuclear-explosion testing by a nation with access to sufficient fissile material. In addition, a tested nuclear weapon design could be transferred to a proliferating nation or group (either deliberately by a sophisticated nuclear state or through espionage), which then might be able to manufacture the weapon without a test. Sophisticated nuclear states could also develop and deploy low-yield tactical nuclear weapons, based on their nuclear-explosion test experience, that could threaten U.S. allies, and the United States must consider such a possibility in its defense planning. In these cases, the committee judges that the United States would not need to return to testing to counter the resulting threat because it already has or could produce weapons of equal or greater capability, based on its own nuclear-explosion test experience. Thus, while such threats are of great concern, the United States would be able to respond to them as effectively under the CTBT as it could without the CTBT.

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[6] The CTBT requires a six-month delay after invoking the supreme national interest clause before a State could conduct a nuclear-explosion test. However, the time needed to prepare a test would be greater than six months.

The final type of threat—that of a new type of strategic weapon—would require the adversary to test at levels detectable by adequately resourced U.S. national technical means and a completed IMS network. This conclusion is based on the best present understanding of nuclear weapons development. As long as the United States sustains its technical competency and actively engages its nuclear scientists and other expert analysts in monitoring, assessing and projecting possible adversarial activities, it will retain effective protection against technical surprises. This conclusion holds whether or not the United States accepts the formal constraints of the CTBT.

1

SAFETY, SECURITY, AND RELIABILITY OF THE U.S. NUCLEAR WEAPONS STOCKPILE

For the U.S. nuclear weapons program, the primary concern related to the Comprehensive Nuclear Test Ban Treaty (CTBT) is whether confidence in the safety, security,[1] and reliability of the weapons can be maintained for the foreseeable future (see Box 1-1) without nuclear-explosion testing. In this chapter we address this issue, emphasizing what has changed since the *2002 Report* (NRC, 2002). We begin with an overview, including the relevant findings of the *2002 Report,* and then describe key changes since that report. This is followed by a summary of the current status and a description of what must be done in the future to maintain a safe, secure, and reliable stockpile without nuclear-explosion testing.

BOX 1-1 The Committee's Judgments about the Future

A treaty of indefinite duration must be evaluated taking into account possible changes over time. Throughout this report, we frequently use the phrase "foreseeable future" in making judgments about the future. By this term, we mean that we have been unable to identify future developments that would alter our judgments and recommendations (In some cases, we caveat a specific judgment by noting that it applies only if our recommendations are followed). At the same time, we are not claiming omniscience about an inherently uncertain future. Because it is possible that conditions we have not foreseen will arise, it is important that the United States establish and maintain appropriate safeguards and, if necessary, be prepared to exercise the withdrawal provisions under the CTBT's supreme national interest article.[2]

In Chapter 1, our use of the phrase "foreseeable future" signifies our assessment that the United States can maintain its existing nuclear weapons with certain safeguards over the long term. This is based on our intimate knowledge of the U.S. nuclear weapons program past, present, and likely alternative futures.

On the other hand, in Chapter 4 we present technical constraints imposed by monitoring and verification on actions that other countries might or might not take. Depending on the country, history shows that this could change over the near term. Thus, we use phrases such as "it is likely that" to leave a healthy margin for such uncertainty (We know what we know, but not necessarily what we do not know). Even so, we conclude that with adequate U.S. safeguards, the actions taken by other countries, although not as predictable as our own, will not likely change U.S. nuclear weapons policy or impose requirements for new weapons "for the foreseeable future."

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[1] The nuclear weapons community uses the term *surety* as an umbrella term covering safety, security, and use control of nuclear weapons. Because the technical details of use control exceed the security classification of this report, the committee does not address use-control issues in the report. To make this clear, the committee uses the term *safety and security* rather than *surety* throughout the text.

[2] CTBT requires a 6-month delay after invoking the supreme national interest clause before a State could conduct a nuclear-explosion test. However, the time needed to prepare a test would be greater than 6 months.

OVERVIEW AND *2002 REPORT* FINDINGS

At the turn of the century, the United States had been observing a self-imposed nuclear-explosion test moratorium for more than seven years and was in the early stages of learning how to maintain its nuclear arsenal in the absence of nuclear-explosion testing. Concerns about the feasibility of this task were an important factor in the 1999 Senate decision not to give its advice and consent to ratification of the CTBT.

The *2002 Report* provided important background and tutorial material on many topics relevant to nuclear weapons. This included an historical perspective on nuclear-explosion testing; a description of the origin of the Stockpile Stewardship Program (SSP); a discussion of the process by which a warhead enters the stockpile and is then maintained; and the factors influencing the safety, security, and reliability of the weapons.

The focus of these sections was on the ability to maintain the existing stockpile in the absence of nuclear-explosion testing. The implied premise was that the military requirements were frozen and that each system would be maintained in a form as close to the original military specifications as possible. Under these assumptions the assessment in the *2002 Report* was that the safety and reliability of the U.S. stockpile could be maintained via careful adherence to past practices and that six measures were most important to accomplishing that purpose:

> We judge that the United States has the technical capabilities to maintain confidence in the safety and reliability of its existing nuclear-weapon stockpile under the CTBT, provided that adequate resources are made available to the Department of Energy's (DOE) nuclear-weapon complex and are properly focused on this task. The measures that are most important to maintaining and bolstering stockpile confidence are:
>
> - maintaining and bolstering a highly motivated and competent workforce in the nuclear-weapon laboratories and production complex,
> - intensifying stockpile surveillance,
> - enhancing manufacturing/remanufacturing capabilities,
> - increasing the performance margins of nuclear-weapon primaries,
> - sustaining the capacity for development and manufacture of the non-nuclear and nuclear components of nuclear weapons, and
> - practicing "change discipline" in the maintenance and remanufacture of the nuclear subsystems. (NRC, 2002, pp. 1, 9.)

The *2002 Report* offered many cautionary notes about the risks associated with any change from the initial configuration of the warhead, especially in the nuclear explosive package. The report was quite positive on the ability to maintain the stockpile without nuclear-explosion testing as long as these risks were respected and the six measures were followed.

CHANGES SINCE THE *2002 REPORT*

The U.S. Stockpile Stewardship Program

At the time of the *2002 Report*, there was uncertainty about the nascent SSP and maintaining the stockpile in the absence of nuclear-explosion testing. The intervening 10 years have seen major successes in the discovery and resolution of significant stockpile issues, as well as notable problems in maintaining the physical and human infrastructure needed for the SSP. The successes indicate that it is possible to maintain a safe, secure, and reliable stockpile into the foreseeable future without nuclear-explosion testing. The problems indicate that future success would be in jeopardy without a continuing commitment to stewardship and the nuclear weapons complex. The issues concerning the sustainability of the enterprise are discussed in Chapter 3 of this report.

A number of changes have occurred since the *2002 Report* was written, some technical and others political with technical implications. Here we discuss some of the most important ones:

- *There have been significant advances in technical knowledge and capability* since the *2002 Report*. These include:
    - studies based on work done at Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL) on plutonium (JASON, 2007), which set a lower limit on pit lifetimes of 85-100 years and which include the resolution of difficult materials issues;
    - the development of peta-scale computational capability and its application to both design and stockpile problems;
    - completion of the National Ignition Facility and initial experiments involving a megajoule of laser energy;
    - completion and operation of other SSP-related major research facilities such as the Dual-Axis Radiographic Hydrodynamic Test Facility *(*DARHT) and the Microsystems and Engineering Sciences Application Facility (MESA); and
    - successful solutions to a number of weapons issues found during surveillance and design work.

  These technical competencies are reflected in the annual letters by the DOE nuclear weapons laboratory directors and the Commander of U.S. Strategic Command (STRATCOM), who conclude that a nuclear-explosion test is not presently necessary to maintain the continued safety, security, and reliability of the stockpile.[3]
- *Production of certified pits* has been demonstrated at Los Alamos, in particular for the W88. This is an important milestone and provides the technical basis for meeting future manufacturing and remanufacturing requirements.
- *The events of September 11, 2001,* occurred too late to have any impact on the *2002 Report*. There have been several subsequent consequences for the nuclear weapons enterprise, some direct and others indirect. First, the skills of people knowledgeable about nuclear weapons have been sought for insight into ways to prevent or mitigate a terrorist nuclear threat. Second, there is increased interest in incorporating additional safety and security features in stockpile weapons, including those requiring changes to the nuclear explosive packages. Further, there have been substantial upgrades of the security posture at sites within the nuclear weapons complex to guard against potential terrorist threats (with concomitant budgetary and operational impacts on the conduct of work).
- *The W87 underwent a successful life-extension program (LEP)* to improve its long-term integrity (NNSA, 2004). The nuclear explosive package was modified to improve weapon reliability.

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[3] The first letters were written in 1996. The Annual Assessment process was established as a result of President Clinton's statements on August 11, 1995, when he announced the decision to negotiate a "zero yield" comprehensive test ban: "As a part of this arrangement, I am today directing the establishment of a new annual reporting and certification requirement that will ensure our nuclear weapons remain safe and reliable under a comprehensive test ban." For more on the Annual Assessment process, see Tyler (2001).

- *The W76 is undergoing a thorough LEP*, with the first production unit having been certified prior to this writing. This LEP stands as an excellent example of both the difficulty of extensive refurbishment (see Box 1-2) and the impressive ability of the SSP to respond to technical challenges. The refurbished primaries include parts newly manufactured to original design specifications. Production of "Fogbank"[4] was initially problematic but appears to have been achieved satisfactorily.
- *There have been a number of technical and programmatic initiatives affecting the nuclear weapons stockpile that have not been implemented* for a variety of reasons. These include the Robust Nuclear Earth Penetrator (RNEP), the Reliable Replacement Warhead (RRW), a broad-scale complex transformation plan, and efforts to recapitalize specific elements of the production complex. In some cases, these did not happen because of technical or political objections; in other cases, they failed for lack of policy guidance; and in many situations, there were not sufficient resources to execute them.
- *Production facilities have continued to age*. Of particular concern are facilities in the Y-12 National Security Complex in Oak Ridge, Tennessee, which conducts uranium processing, and the Chemistry and Metallurgy Research (CMR) Facility at LANL, which provides support for both pit production and plutonium research. These facilities are old and at risk of being shut down from time to time for safety reasons. Their replacement has been delayed due to budget pressures and the fact that the appropriate direction, scale, and scope of the future nuclear weapons program was not yet settled. The FY 2011 budget proposes full funding for both the Uranium Processing Facility (UPF) at Y-12 and the Chemistry and Metallurgy Research Replacement facility (CMRR) at the Los Alamos National Laboratory (LANL) (the FY 2012 request formally deferred CMRR for at least 5 years). Both facilities are also explicitly called for in the 2010 Nuclear Posture Review (U.S. DOD, 2010a, p. 42). In November 2010, the White House announced that the President's 2012 budget would include additional funding for these two major facilities and stated, "Funding requirements will be reconsidered on an ongoing basis as the designs mature and as more information is known about costs" (Public Law 111-84 Update, 2010, p. 6).

- *Two major changes to the surveillance program have begun since the* 2002 Report.[5]
    1. The Enhanced Surveillance Program (ESP) was established with the aim of enhancing the non-destructive diagnostic tools available for surveillance.
    2. The Surveillance Transformation Project (STP) was created with the goal of collecting data that is more relevant to the needs of today's stockpile stewardship--for example data that can help quantify aging trends while dismantling fewer units of each warhead type each year.

  Although the goals and ideas behind ESP and STP are appropriate, there has not yet been adequate follow-through on budgetary resources and detailed plans needed for implementation.[6]
- *LANL and LLNL have continued plutonium (Pu) aging work* and have concluded that, although no critical aging issue had been identified, further work on certain aging topics

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[4] Fogbank is a material used in the W76 warhead. It was manufactured during the 1980s, and after production ceased in the mid-1990s, substantial effort was required to recertify the production process. This recertification was completed in 2008. For additional details, see LANL (2009); see also: *http://www.lanl.gov/orgs/padwp/pdfs/nwj2_09.pdf*.

[5] Surveillance funding declined from $195 million in FY07 to $158 million in FY09. The FY11 budget increases this amount to $239 million, which the White House has committed to sustain for the next several years. Public Law 111-84 Update, p. 3

[6] See also the discussion of surveillance on p. 23.

(e.g., phase stability, engineering behavior, hostile environments, and corrosion) is warranted to reduce uncertainties, explore whether there are any further materials issues, and develop any associated mitigation strategies.

- *A shift has taken place in the way in which the NNSA and the Laboratories formally analyze stockpile systems*. In the *2002 Report,* the key element in evaluating (or enhancing) warhead performance was primary margin (the degree to which the primary yield exceeded the minimum level needed to provide the required secondary yield). Since that time, this concept has been extended to other aspects of a weapon's performance and is now practiced within a framework known as Quantification of Margins and Uncertainties (QMU).[7] Thus, for example, when assessing a proposed LEP, the QMU analyses provide a way of quantitatively comparing various options in an objective, systematic, and transparent way. QMU also provides a metric for the stewardship program, whose goal is to use the various scientific tools to reduce uncertainties and thus increase confidence in the ability to predict performance, safety, security, and reliability in an existing or modified weapon.
- *A significant shift in the perspective on stockpile management has occurred since the* 2002 Report. The conclusion in 2002 was that the nuclear stockpile could be maintained in the absence of nuclear-explosion testing and that changes, especially to the nuclear explosive components, were high-risk and should be avoided. Since that time, there have been improvements in technical understanding as well as an increased emphasis on nuclear warhead safety and security. As a consequence, the United States is now considering as serious options changes to the nuclear explosive package incorporating additional safety and security features and/or increased performance margins[8] in addition to the original LEP approach of refurbishment (see Box 1-2). In particular, the possibility of reuse of nuclear components from other tested systems (other than the one under maintenance) and/or nuclear component design changes (within the range of U.S.-tested designs) that improve the safety, security, and reliability could be credible and technically feasible approaches. We caution that certification of some safety and security improvements under consideration would require detailed analysis on a case-by-case basis and, in some cases, greater scientific understanding than now exists. The 2010 Nuclear Posture Review (NPR) states that the United States will "study options for ensuring the safety, security, and reliability of nuclear warheads on a case-by-case basis…. The full range of LEP approaches will be considered: refurbishment of existing warheads, reuse of nuclear components from different warheads, and replacement of nuclear components." The NPR goes on to state a "strong preference" for refurbishment or reuse, with replacement considered only where critical goals could not otherwise be met (U.S. DOD, 2010a, p. 39).

Finally, in addition to releasing its Nuclear Posture Review, the Administration has concluded a "New START" Treaty with Russia and ratified it on February 2, 2011. The follow-on to the expired START I Treaty between the United States and the Russian Federation will reduce deployed strategic nuclear warheads on each side to 1,550. The Nuclear Posture Review, the third since the end of the Cold War and first to be unclassified, includes new

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[7] QMU requires the quantitative ("Q") assessment of performance in terms of margins ("M"—the difference between the best-estimate value and the threshold value for key performance characteristics) and uncertainties ("U"—the amount by which the best-estimate and threshold values are uncertain). When the ratio of M to U is well above one, then there is high confidence that performance will be acceptable, while an M/U ratio closer to or less than one indicates lower confidence. See NRC (2008).

[8] For some weapons, higher margins are key to confidence in performance under certain circumstances, if they can be achieved without an accompanying increase in uncertainties.

guidelines for U.S. nuclear weapons policy. The report outlines five key objectives for U.S. nuclear posture (U.S. DOD, 2010a, p. 2.):

1. Preventing nuclear proliferation and nuclear terrorism.
2. Reducing the role of U.S. nuclear weapons in U.S. national security strategy.
3. Maintaining strategic deterrence and stability at reduced nuclear force levels.
4. Strengthening regional deterrence and reassuring U.S. allies and partners.
5. Sustaining a safe, secure, and effective nuclear arsenal.

Elaborating on the fifth objective, the NPR states that, as long as nuclear weapons exist, the United States will sustain safe, secure, and effective nuclear forces, which will continue to play an essential role in deterring potential adversaries and reassuring allies and partners around the world.

BOX 1-2 Options for Extending the Life of Nuclear Warheads

Under any life-extension plan for a warhead, components outside of the nuclear explosive package (NEP) have been, and will be, replaced with upgraded versions—this is not controversial. For the NEP itself, the terms "refurbishment," "reuse," and "replacement" are frequently used in the discussion of options for life-extension programs. However, their definitions are not always clear and are not universal. Below, the committee defines these terms as used in this report:

- *Refurbishment* describes the case in which individual components in the NEP are either retained for continued use or replaced with components of nearly identical form, fit, and function.
- *Reuse* describes the case in which pits and secondary components from *different,* previously fielded warhead designs are introduced into the warhead. This usually implies that the pits and/or components are taken from existing surplus stocks, but if such parts did not exist in sufficient number, the committee would extend "reuse" to include parts newly manufactured to nearly identical specifications.
- *Replacement* describes the case in which pits and/or secondary components introduced into the warhead are based upon previously tested designs but may differ in some respects from such designs.

Finding 1-1: The technical capabilities for maintaining the U.S. stockpile absent nuclear-explosion testing are better now than anticipated by the *2002 Report*.

Current Status of U.S. Nuclear Weapons and the Stockpile Stewardship Program

The number of deployed U.S. nuclear weapons has continued to decrease (through the vehicle of the Strategic Offensive Reduction Treaty [SORT], also called the Moscow Treaty of 2002) and, as of December 31, 2009, stood at 1968 (U.S. Department of State, 2010a) operationally deployed strategic warheads. The "New START" Treaty signed in Prague on April 8, 2010 (and ratified by the United States on February 2, 2011) by the United States and the Russian Federation reduces deployed strategic nuclear warheads on each side to 1,550, down from the 2,200 limit set by the Moscow Treaty (U.S. Department of State, 2010b and Public Law 111-84, 2010).

The total stockpile has also decreased. As of September 30, 2009, the U.S. stockpile of nuclear weapons consisted of 5,113 warheads, a 75-percent reduction from the number in the stockpile when the Berlin Wall fell in late 1989, and a 50-percent reduction from the stockpile existing at the time of the *2002 Report*. Several thousand additional nuclear weapons are currently retired and awaiting dismantlement (U.S. DOD, 2010b).

The stockpile consists of nuclear explosives that can be mounted into one or more of three types of delivery systems: aircraft, land-based missiles, and sea-based missiles. Traditional terminology divides the stockpile into strategic and tactical components.[9]

- Strategic forces include: Bombers (carrying gravity bombs and air-launched cruise missiles, ALCMs), land-based missiles (intercontinental ballistic missiles, ICBMs), and submarine-launched ballistic missiles, SLBMs), together forming the so-called “traditional nuclear triad.”
- The so-called tactical component includes gravity bombs for deployment on U.S. and NATO tactical aircraft, as well as a small number of non-deployed submarine-launched cruise missiles (SLCMs).[10]

The United States has seven main nuclear warhead designs in its active stockpile today:[11] B61 (tactical or strategic bomb), B83 (strategic bomb), W76 (SLBM warhead), W78 (ICBM warhead), W80 (ALCM/SLCM warhead), W87 (ICBM warhead), and W88 (SLBM warhead). Each of these designs was certified before it was introduced into the stockpile and is maintained in operational status with a team examining and evaluating it to support the annual assessment of the stockpile.

Stockpile Stewardship Program Components

The SSP has a broad mandate for maintenance, evaluation, and improvement of the stockpile. Carrying out this mandate requires a broad range of facilities and capabilities:

- *Surveillance (including dismantlement, maintenance, refurbishment and assembly of nuclear weapons)*, centered at Pantex and Y-12;
- *Experimental research,* primarily located at LANL, LLNL, Sandia National Laboratories (SNL), and the Nevada Test Site (NTS);[12]
- *Design, modeling and simulation,* including the Advanced Simulation and Computing (ASC) program at the DOE nuclear weapons laboratories; and

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[9] Although the difference between a tactical and strategic weapon can be somewhat arbitrary, defined by treaty language or delivery capability, and all nuclear weapons can be viewed as strategic in the sense that they alter the nature of the conflict, this report will continue to distinguish between and utilize the terms *strategic* and *tactical*. In this report, a “new type” of strategic weapon refers to a strategic weapon whose design falls outside of the range of those in a country’s nuclear-explosion test experience. See further discussion of the distinction in Chapter 4 and in Box 4-2.

[10] Cruise missiles (Tomahawk Land Attack Missiles/Nuclear, TLAM/N) were removed from U.S. Navy vessels as a result of the President’s 1991 Nuclear Initiatives, but the United States has the option to redeploy them on attack submarines if it decides that action is necessary. The 2010 Nuclear Posture Review eliminates TLAM/N.

[11] B designates bomb; W designates warhead. There are multiple modified forms of some of these designs, especially the B61.

[12] The NTS was recently renamed the Nevada National Security Site (NNSS); however, the acronym *NTS* will continue to be used in this report due to its familiarity to most readers.

- *Nuclear weapons production* at LANL, Pantex, and Y-12, for components involving special nuclear material; Savannah River Site (SRS) for tritium production; and SNL and the Kansas City Plant for non-nuclear components.

The DOE nuclear weapons laboratory directors and the STRATCOM Commander rely on the SSP to provide the information underpinning their conclusions in the annual assessments of the nuclear weapons stockpile.

Surveillance

The Surveillance Program pulls deployed warheads from the stockpile and conducts non-invasive testing (e.g., x-ray) on some and invasive testing (disassembly) on others. Both nuclear and non-nuclear components are examined. A vigorous surveillance program is an essential mainstay of the nuclear weapons effort because it allows NNSA to examine warheads for anticipated degradation from known age-related processes and for unanticipated problems related to age or production defects. The United States initiated its stockpile surveillance and assessment program in 1958 when sealed pits were introduced into stockpile weapons. The original surveillance program was oriented primarily toward finding production defects. The number of warheads of each type to be inspected each year was chosen so that if a particular defect occurred in the warheads, there would be a high probability of inspecting a defective unit within a two-year interval. In recent years, it has been proposed that this original program be replaced with the Surveillance Transformation Project (STP), which applies a more targeted data collection to fewer units.

Assessments to date have been made with acceptable uncertainties, but assessment uncertainties will increase over time unless the surveillance program begins to provide the needed quality and type of new data (Congressional Commission, 2009; JASON, 2009). The committee learned that the surveillance program for the past several years has not been providing the timely data that the warhead design teams will need for confident assessments of aging and other effects into the future. Because surveillance is so central to successful stewardship, the committee is gravely concerned about any possible shortcomings in the activities documenting the health of the stockpile. NNSA has advised the committee that the President's FY 2011 budget will rectify resource shortfalls. The committee has not evaluated the NNSA plan and is principally concerned with long-term sustainment of the necessary efforts.[13] However, in a letter of December 1, 2010, to Senators Kerry and Lugar, the directors of the 3 weapon laboratories state that "… the proposed budgets provide adequate support to sustain the safety, security, reliability and effectiveness of America's nuclear deterrent within the limit of 1550 deployed strategic warheads established by the New START Treaty with adequate confidence and acceptable risk" (Miller et al., 2010).

Finding 1-2: Future assessments of aging effects and other issues will require quantities and types of data that have not been provided by the surveillance program in recent years.

Experimental Research Facilities

The SSP has a number of large-scale experimental facilities that to some extent simulate phenomena that occur during a nuclear explosion. During the past several years major

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[13] For White House commitments to maintain adequate surveillance funding; see Public Law 111-84 Update, p. 3.

advances have been made in these facilities, and they have become integral parts of the present and future stewardship program. These include:

National Ignition Facility (NIF). NIF was dedicated on May 28, 2009, at LLNL. Its goal is to provide a thorough scientific understanding of the behavior of materials during conditions similar to those in a nuclear explosion, and to carry out both ignition and weapons physics experiments to study dynamic phenomena that occur during such explosions. A major objective is to achieve ignition (i.e., thermonuclear burn) because this will enhance the U.S. ability to study such phenomena. The early experiments since the NIF dedication have demonstrated that the facility is operating well. All 192 beams have been fired a number of times and total power levels on target have reached the one megajoule (MJ) level (of the ultimately planned 1.8 MJ, or 3 MJ of green light), with many of the issues important for ignition already being tested. The current emphasis is on executing the National Ignition Campaign (NIC) with the goal of achieving ignition within the next two years. Throughout this period, there will also be a major effort aimed at detailed comparison of the simulation codes with experiments. Subsequent to the NIC, the facility will broaden its program to act as a national user facility with a portion of the experimental time made available to the general scientific community. Concurrently, the NIF will be instrumental in making progress on the major weapons initiatives in boost and energy balance, as well as testing many aspects of weapons design codes.

- *Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility.* This facility at LANL is a complete radiographic system with elements that combine to produce multiple images of test objects as they evolve during an implosion, with unprecedented resolution. Images from the dual axes allow scientists to check the implosion symmetry of weapon mockups because images can be taken from orthogonal directions at the same time. The first axis has been operational since 1999, and the first hydrodynamics experiment using both axes was successfully executed on December 3, 2009.

  Image data and data from other measurements made during the hydrodynamic tests are compared with computer calculations to assess the ability to predict the performance of systems that are similar to real weapon systems. Scientists at DARHT can now follow the implosion's progress[14] until almost the explosion time of a real weapon and compare the pictured component positions with the predictions of computer simulations. In addition, DARHT can be used to study basic weapons physics with scaled experiments and to develop a deeper understanding of detonations, hydrodynamic behavior, and materials properties. This information is then incorporated into new simulation computer codes developed under the Advanced Strategic Computing program.
- *Microsystems and Engineering Sciences Application (MESA).* MESA was constructed at Sandia National Laboratories to provide advanced simulation tools, microsystems, and nanotechnology capabilities for weapons engineering and related national security projects. It consists of three elements: the Microelectronics Development Laboratory, the Microsystems Laboratory, and the Weapons Integration Facility. It was dedicated on August 23, 2007.

  Sandia has the primary role of developing and designing the electronic systems that operate nuclear warheads. Key components of those systems are radiation-hardened microelectronics, devices that are designed, qualified, and fabricated in the MESA facilities. In addition to fabricating electronic circuits, the MESA facility also makes microelectromechanical elements for advanced security systems, sensors, guidance systems, and other applications. The complex also includes the world's most complete

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[14] Using a simulant for weapon-Pu.

compound-semiconductor fabrication facility. This will produce advanced optoelectronic and custom electronic components, communications, and other emerging technologies. It is one of the few microelectronic facilities that is fully integrated with a state-of-the-art high performance computing capability.

Other Facilities. In addition to NIF, DARHT, and MESA, a number of other smaller facilities contribute substantially to the stewardship program.

- The *OMEGA laser* at the University of Rochester has been important in providing data from high-energy-density experiments and in preparing the technical path for NIF, and it continues to be a complementary facility.
- The *Z Machine* at Sandia provides a pulsed power capability that enables scientists to probe many relevant topics in high energy density science.
- Both the Joint Actinide Shock Physics Experimental Research (*JASPER)* Facility and the underground *U1a Complex* at the Nevada Test Site are dedicated to dynamic experiments on the properties of uranium and plutonium.
- In addition, each of the three laboratories has special-purpose facilities, such as the High Explosives Applications Facility (HEAF) for high explosive work at LLNL, the Los Alamos Neutron Science Center (LANSCE) for neutron experiments, and various machines that are used for work on weapon vulnerability in hostile environments at Sandia and NTS.

Design, Modeling, and Simulation

Advanced Simulation and Computing (ASC)--Even during the nuclear weapon testing era, computer simulation of nuclear weapons performance was the primary way in which nuclear weapons were designed. In the absence of nuclear-explosion testing, advanced computing serves as the means for putting all of the nuclear weapons information together to evaluate the impact of a surveillance finding, assessing the impact of a proposed refurbishment or modified design, and comparing experiments on facilities such as NIF or DARHT with calculations made with weapons codes (testing the merits of both the code and the designer).

In the early phases of the SSP, the primary goal of the advanced computing program was to establish a high resolution, 3-dimensional (3-D) weapons-simulation capability, because assessing age-related problems or other issues tended to involve “off-center” defects such as corrosion and cracks that could not be modeled in a 2-D calculation. Concurrently, the execution of an LEP required detailed design calculations with sufficient detail to provide confidence in the refurbishment. The long-term goal in the computing program is to improve predictive capability with quantitatively assessed uncertainties so that there will be even higher confidence in proposed warhead modifications for an LEP, including the incorporation of new safety and security or performance features.

Since the mid-1990s, inception of the Advanced Simulation and Computing Initiative (ASCI, the predecessor of ASC), the computing capability available to weapons designers has increased by a factor of approximately one hundred thousand, as shown in Figure 1-1. In recent years the strategy has been to pursue “capability” machines for the most detailed calculations, “capacity” machines for cost-effective high throughput of smaller calculations, and “advanced architecture” machines to explore and influence potential game-changing technologies. Each kind of machine plays an important role in the weapons program. It is possible that the “capability” and “advanced architecture” machines may be one and the same in future acquisitions. A recent program change is to have a single “capability” machine (on which the most detailed and demanding calculations are carried out) accessible by all three Laboratories on a secure network. This has the virtues of much greater efficiency and reduced cost, while providing a common framework for comparison. The current computer is located at LLNL, with the next one to be sited at LANL, with Sandia participating in the development.

"Capacity" machines—less powerful but less expensive than capability ones—do much of the "get-ready" calculations to prepare for full-design simulations, and a new tri-laboratory architecture is now used by all the laboratories. Advanced architecture machines tend to have great speed but much less flexibility in the kinds of problems on which that speed is effective. Thus, existing computers at LLNL and LANL, and two new computers planned for LLNL in the next two years, can carry out valuable, special-purpose calculations (often focused on basic weapons science issues) while scientists explore their adaptation to direct design work.

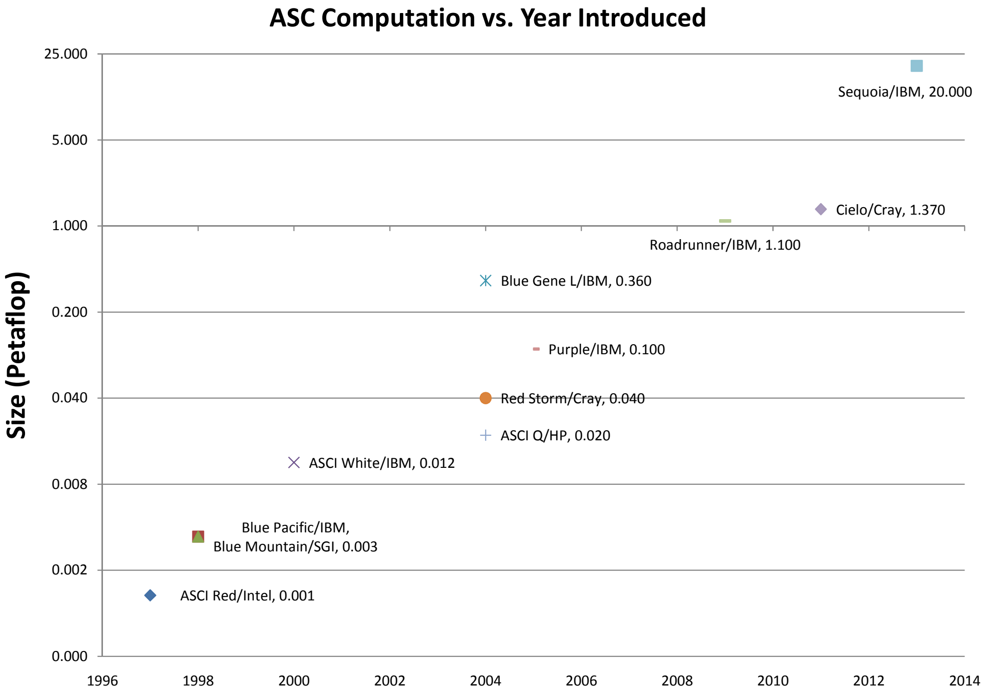

FIGURE 1-1: Advances in computation power in the Advanced Simulation and Computing (ASC) program since 1996. SOURCE: NNSA

Exascale computing, the next major threshold, will not be achieved by a natural evolution of existing technologies. Basically, the elements of the modern supercomputer—thousands of individual, interconnected smaller computers—are continuing to gain in speed but not adequately in memory density. At the same, time the power requirements are becoming unsupportable in cost and cooling. These technology barriers will become limiting factors over the next 5 years, before exascale-class systems will be reached. Consequently, multiple hardware and software paths towards exascale are being pursued, some in partnership with other organizations, such as DOE's Office of Science.

Nuclear Weapons Production Complex

The nuclear weapons production complex includes a number of sites that deal with different elements of weapons systems:

- Pantex Plant (high explosives, assembly and disassembly of weapons);
- Y-12 National Security Complex (uranium and other components);
- LANL (detonators and plutonium activities including pit production);
- Savannah River Site (tritium production and gas transfer systems);
- SNL (neutron generators); and
- Kansas City Plant (electronic, electrical, and mechanical components, including gas transfer systems).

Immediate needs include modern facilities that support uranium and plutonium science, and provide capabilities to produce pits and uranium components for stockpile weapons. The two sites responsible for production activities with special nuclear materials, Y-12 and the plutonium complex at LANL, rely on facilities that in some cases date from the early days of the Cold War, and it is both expensive and difficult to maintain them at modern safety and security standards. As was mentioned earlier in this chapter, NNSA has detailed modernization plans to build replacement facilities, but replacement of the main facilities has been delayed due to budget pressures and the fact that the appropriate direction, scale, and scope of the future nuclear weapons program was not yet settled. DOE and DOD officials have testified that the United States maintains a large number of reserve warheads because of the inability to manufacture significant numbers of new warheads in response to changed geopolitical circumstances.[15]

- *Y-12.* This site is responsible for the manufacture of secondaries, including uranium components. NNSA's plan is to consolidate the storage areas for highly enriched uranium (HEU) at the HEU Materials Facility (HEUMF), which has been built, and to build a uranium processing facility (UPF) to replace several 50-year-old facilities. The projected cost for this plan is estimated as $4.2-6.5 billion[16] to create a production capacity of 80 units per year. The benefits of the new Y-12 facility would be a smaller footprint, leading to much lower security costs, a safer facility, and one that is appropriate for a modern stockpile size (compared with the production requirements of 1,000 per year during the Cold War). However, the lead time to develop an operational new plant is a decade or more, so the overall strategy to ensure the supply of secondaries as needed for LEPs is still under active discussion.
- *Chemistry and Metallurgy Research Facility (CMR)*. LANL facilities have long-term responsibility for the plutonium research and development and pit production work. CMR was completed in 1952 and supports a broad range of plutonium research and development activities as well as pit production. It is recurrently on the verge of being shut down because of safety issues, and there is a plan to replace it with a modern set of facilities, the CMR Replacement complex (CMRR). As with Y-12, the timescale

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[15] The 2010 Nuclear Posture Review discusses the need for non-deployed warheads as a "hedge against technical or geopolitical surprise" and notes that there are currently more warheads than are required. It further states that "progress in restoring NNSA's production infrastructure will allow those excess warheads to be retired" (U.S. Department of Defense, 2010a, p. 38).

[16] Public Law 111-84 Update, p. 6.

to complete the facility is on the order of a decade. The total project costs are estimated at $3.7–5.8 billion.[17]

- *Pit Production Facility (PF-4)/Technical Area-55.* The LANL plutonium production facility (PF-4) is the only one in the United States that can produce war-reserve quality plutonium pits for the stockpile. Recently, LANL has demonstrated its capability through production of a certified W88 pit. Current capacity at LANL is stated to be 6-10 war-reserve pits per year. With major infrastructure investments, including completion of CMRR, the maximum war-reserve production rate of 80 pits/year could be achieved. Relatively modest investments in upgrades to PF-4 could result in a pit reuse capacity of at least 40 war-reserve pits per year.

The President's FY 2011 budget requested funding for construction of both the UPF at Y-12 and CMRR at LANL; the FY 2012 request formally deferred CMRR for at least 5 years.

Life-Extension Programs (LEP)

Since the *2002 Report,* there has been considerable discussion about the changes that accumulate over a warhead's lifetime. In such discussions, four distinct categories of changes should be kept clearly separated:

1. Changes induced by aging;
2. Changes from the certified design introduced during manufacturing;
3. Changes in the assessed performance of the certified design driven by improved understanding or more careful assessment; and
4. Deliberate physical changes (made through an LEP or another program of alteration).

Changes in all four categories have taken place in the stockpile. The appropriate response depends on the category and other details. When an aging-induced change is assessed to reduce confidence to an unacceptably low level, a deliberate physical change is required to restore the warhead's original performance characteristics. However, aging-induced changes do not argue for one kind of LEP over another, because a LEP of any kind can reset the "aging clock" to zero. Discovery of a manufacturing error prompts an assessment of how many units it may affect and the creation of an acceptable solution. Changes in the assessed performance of a design could lead to modification of certified performance characteristics, modification of change-out intervals for limited-life components, or a decision to remove the weapon from the stockpile. Deliberate physical changes are made when necessary and are made in the course of LEPs, which take place for a given NEP only once every few decades.

The committee investigated concerns that have been expressed about accumulated changes in the stockpile from aging and other sources. In probing to understand these concerns, the committee was impressed by the degree to which technical issues encountered to date have been resolved by the U.S. nuclear complex. In their discussion with the committee, the laboratory directors from Livermore, Los Alamos, and Sandia all indicated that there is no evidence of any technical issues that cannot be resolved with the present competency (LLNL, October 2009, personal communication). In their annual assessment letters from 2009, the laboratory directors all indicate that underground nuclear-explosion testing is not presently required to maintain the certification of weapons in the stockpile. They expressed concerns, however, about financial and other constraints on the technical program, deferred life extension decisions and activities, and shortfalls and delays in surveillance data. They warn that aging and

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[17] Ibid.

other accumulated changes to weapons in the stockpile will erode confidence in weapon performance in the future unless surveillance programs are enhanced and given priority, LEPs are conducted in a timely way, and investments in the physical and intellectual infrastructure of the nuclear weapons enterprise are increased.

The committee offers several observations on concerns about aging and accumulated changes. First, each annual assessment letter stated that nuclear-explosion testing was not necessary at the time of its writing to resolve technical issues. Second, changes caused by aging should be discussed separately from other categories of changes. The existence of age-induced changes is not a surprise. We have long known that they would occur and that, if unaddressed, “continuing accumulation of aging changes” would reduce reliability and effectiveness. However, they can be eliminated through any of the LEP options that have been considered, if funded and performed as needed. Third, it is easy to misinterpret the phrase “accumulated effects of weapons changes” as referring to something that is in addition to aging-induced changes. In fact, aging-induced changes are the only physical changes that are accumulating year to year in the nuclear explosive packages (NEPs) in the stockpile. Deliberate physical changes are carefully designed to have at most a minimal negative impact on confidence, and in many cases are assessed to improve confidence. Fourth, manufacturing errors should be discussed separately from changes in assessed performance of a given design, for they have different causes and different solutions.

Finding 1-3: The committee judges that Life-Extension Programs (LEPs) have been, and continue to be, satisfactorily carried out to extend the lifetime of existing warheads without the need for nuclear-explosion tests. In addition to the original LEP approach of *refurbishment*, sufficient technical progress has been made since the *2002 Report* that *re-use* or *replacement* of nuclear components can be considered as options for improving safety and security of the warheads. The assessment of which of the spectrum of options is most appropriate for a given warhead needs to be made on a case-by-case basis because the benefits and risks depend on the warhead under consideration. Replacement of non-nuclear components has always been an option.

Workforce

The workforce and management of the nuclear weapons complex are essential elements of maintaining the safety, security, and reliability of the U.S. stockpile. To sustain a technically competent, motivated and capable workforce, the weapons laboratories will need to employ some degree of innovation, for example by developing a work structure that draws from a broader base of nuclear-capable personnel to work on more diverse national security projects. To be successful, such activities must be encouraged and supported by NNSA and laboratory management as well as Congress and the Administration. These topics are addressed further in Chapter 3.

The discussion in the above sections leads to the following finding and recommendation:

Finding 1-4: Provided that sufficient resources and a national commitment to stockpile stewardship are in place, the committee judges that the United States has the technical capabilities to maintain a safe, secure, and reliable stockpile of nuclear weapons into the foreseeable future without nuclear-explosion testing. Sustaining these technical capabilities will require at least the following:

- *A Strong Scientific and Engineering Base*. There must be continued adherence to the principle that the ability to assess and certify weapons rests on technical understanding of weapons phenomena, data from past nuclear-explosion tests, computations, and data from past and ongoing experiments. Maintaining both a strategic computing capability and modern non-nuclear-explosion testing facilities (for hydrodynamic testing, radiography, material equation-of-state measurements, high explosives testing, and fusion experiments) is essential for this purpose.

- *A Vigorous Surveillance Program*. An intensive surveillance program aimed at discovering warhead problems is crucial to the health of the stockpile.
- *Adequate Ratio of Margin to Uncertainty.* Performance margins that are sufficiently high, relative to uncertainties, are key ingredients of confidence in weapons performance.[18]
- *Modernized Production Facilities.* Most of the nuclear weapons production facilities are old (50 years in some cases) and are both difficult and costly to operate in accordance with modern standards of safety and security.
- *A Competent and Capable Workforce.* Nuclear weapons work (e.g., the SSP) is key to meeting a range of challenges in the broader national security landscape. Exploration of these broader areas (e.g., nonproliferation programs, render safe, etc.) can provide opportunities for intellectual stimulation and professional development that will attract a diverse, capable workforce. It is equally important to ensure that the Department of Defense, particularly the Defense Threat Reduction Agency, the Navy's Strategic Systems Project Office, and the Air Force's Ballistic Missile Organization maintains a technically competent workforce (Congressional Commission, 2009; U.S. Secretary of Defense Task Force on DOD Nuclear Weapons Management, 2008; Defense Science Board, 2008).

Recommendation 1-1: To address each of the essential elements of stockpile stewardship listed in Finding 1-4, NNSA, working with the Administration and Congress as appropriate, should:

- *Maintain a continuing dynamic of experiments linked with analysis.* Both are essential to maintaining the capability to render judgments about stockpile issues.
- *Maintain a vigorous surveillance program* that is systematic; is statistically based where possible; and continuously reflects lessons learned from annual surveillance, LEPs, fixing problems, and science-based analysis. Nondestructive tools and experimentally validated computational analysis should be developed and applied to introduce more predictive capability into the surveillance system.
- *As part of each LEP, explore options for achieving adequate margins* through reuse or replacement scenarios in addition to refurbishment, to determine how best to meet military, technical, and policy objectives. Assess uncertainties associated with each scenario.
- *Develop and implement a long-term production facility modernization plan.* This should include maintaining a plutonium science and production capability, including the ability to produce various types of pits for weapons in the stockpile.
- *Broaden the base of its nuclear expertise by involving nuclear-capable personnel in related national security projects* (nuclear forensics, intelligence, threat reduction programs, basic science applications of stewardship activities, etc.).

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[18] Some of today's systems already have relatively high margin-to-uncertainty ratios; others are relatively low.

TEST READINESS

The *2002 Report* did not evaluate test readiness in any detail. Since that report was issued, there have been a number of developments.

During the 1999 consideration of CTBT ratification, the Administration proposed the following as a safeguard: "The maintenance of the basic capability to resume nuclear test activities prohibited by the CTBT should the United States cease to be bound to adhere to this Treaty." The committee presumes (and would favor) inclusion of such a safeguard when CTBT is reconsidered. Underground nuclear-explosion testing requires a suitable test site, a set of specialized equipment and infrastructure, and a body of specialized knowledge. As long as the NTS remains in government possession and free from any construction that would interfere with nuclear-explosion testing, reconstituting a "basic capability" will, in principle, always be feasible. The question is, therefore, how much lead time the United States should assume would be necessary for a resumption of testing.

Currently, NNSA is required by a 1993 Presidential Decision Directive (PDD-15, "Stockpile Stewardship") to maintain the ability to conduct a nuclear test within 24-to-36 months of direction by the President to do so.[19] This is the only extant guidance on the timing of test readiness. The 2010 Nuclear Posture Review is silent on the subject of test readiness. The 2001 Nuclear Posture Review called for shortening this period. Although the Administration did not specify a time, NNSA internally adopted a goal of being ready to conduct a test in 18 months (Brooks, 2005). Congress declined to fund 18-month readiness and directed (in report language accompanying the FY 2006 Energy and Water Development Appropriations Act) that the Administration maintain the ability to conduct an underground nuclear-explosion test within 24 months. Since that time, funding reductions by Congress and competing priorities within NNSA have further reduced funding for test readiness.

From the technical perspective, there are four major reasons why a limited number of tests might be required:[20]

- To develop a weapon with new technical characteristics that could be validated only by testing.
- To confirm a stockpile problem or certify a solution.
- To ensure understanding of actions taken by others (technical surprise).
- To verify render-safe procedures.

NNSA currently assesses that it has the capability to conduct a test to meet very limited technical objectives within 18 months of a request to do so, but only if some "domestic regulations, agreements and laws" were to be waived.[21] With greater confidence, NNSA assesses that it could conduct a test and achieve specific technical objectives within 36 months

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[19] Discussion of required lead times is based on *Nuclear Test Readiness: Report to Congress* (U.S. DOE, 2009). Note that NNSA assessments assume the conduct of only a single test or very short series; NNSA is not maintaining any capability to resume routine, sustained nuclear testing.

[20] Some would add weapons effects tests; the committee judges these as less significant. In any case, such tests are sufficiently complex that designing them is likely to be the pacing item in preparing for a test. A final possibility is a test to demonstrate resolve or one conducted in response to testing by another State. In such a case, the United States would presumably wish to conduct the test as rapidly as possible but would have no specific technical objectives. The committee considers such testing outside the scope of its charter.

[21] "Currently, the NNSA does not have the capability to conduct a nuclear test that would be fully compliant with domestic regulations and laws with[in] 18 months of an order by the President to do so" (U.S. DOE, 2009).

of a decision. However, because of technical uncertainty, NNSA cannot say with “high confidence that [it] remains within the required 24-36-month required time window for highly diagnosed and authorization-driven hypothetical nuclear tests.” The committee also heard the view that investing annually in maintaining aging test diagnostic equipment and other test-related capabilities may not be the best possible use of funds. If events led to a decision by the United States to resume testing, presumably the crisis would be severe enough to justify the identification of funding specifically to support testing. Such funding would allow for the procurement of the best available new equipment. The pacing item in conducting an underground test is likely to be regulatory, not technical. For example, the National Environmental Policy Act (NEPA) requires extensive analysis that is often subject to court challenge.[22] Similarly, Title 10 of the Code of Federal Regulations (CFR) Part 830, *Nuclear Safety Management*, requires NNSA to complete various safety analyses before conducting a test. In addition, Congressional funding approval would be required. Some—and perhaps all—of these regulatory requirements could be waived by the President (or by legislation) if the situation were considered urgent enough to do so.[23] Assuming waivers of regulations and laws, the only legal limit on how rapidly the United States could conduct a test would be the obligation in Section IV of the Protocol to the Threshold Test Ban Treaty of 1974 to notify the Russian Federation 200 days in advance of a nuclear-explosion test.

Development of a weapon with new military characteristics would take significantly longer than 24-36 months. Thus the important limit appears to be the need, however remote, to conduct a test to ensure the health of a weapon important to the stockpile. The pre-2006 NNSA readiness goal of 18 months was based on analysis indicating that, when the United States was routinely testing prior to 1993, it would normally take about 18 months to develop and field a nuclear-explosion test designed to obtain technical data (U.S. DOE, 2009).

For nearly a decade, Congress has consistently reduced or denied funding for test readiness. NNSA elected to seek no funding for Fiscal Year 2010, and the President’s fiscal year 2011 budget has no dedicated funding for test readiness. As a result, NTS is experiencing many of the same problems that are seen in other elements of the nuclear weapons complex, including age-related degradation of physical assets and diagnostic equipment, lack of maintenance, outdated technology, and lack of experienced and trained personnel for critical positions. A recent report by the Department of Energy Inspector General concluded that, “there is a risk that physical assets and diagnostic equipment could not be made ready to support an underground nuclear test within the required three-year window” (Sedillo, 2009). The Inspector General attributed these problems to lack of budgetary support.

Although SSP provides many of the capabilities required to conduct a nuclear-explosion test, the committee believes that continued use of the NTS for sub-critical experiments and for other complex, high-hazard operations also helps maintain test readiness. It is important to note that some capabilities must be explicitly maintained in addition to a robust SSP. NNSA identified the following in presentations to the committee (U.S. DOE, 2009):

- Preserve the Nevada Test Site's ability to host a nuclear-explosion test;
- Support containment capability unique to underground nuclear-explosion testing;

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[22] In the specific case of NEPA, Title 40 of the Code of Federal Regulations (CFR) Part 1506.11, *Emergencies*, authorizes alternate arrangements with the approval of the White House Council on Environmental Quality in cases “where emergency circumstances make it necessary to take an action with significant environmental impact without observing the provisions of these regulations.”

[23] Recently a task force, “which included all three NNSA national laboratory directors, concluded” that “a very limited test to signal the readiness of the U.S. nuclear deterrent or respond to another nation’s test, could be conducted in 6 to 10 months, but such a test is not a component of stockpile stewardship” (U.S. DOE, 2011).

- Maintain the integrity of the seismic analysis of southern Nevada;[24]
- Maintain the test-specific parts of radiochemistry infrastructure and drill-back capability;
- Support fast readout requirements; and
- Maintain a library of testing methods, rack designs, procedures, processes, etc.[25]

Finding 1-5: To maintain a test readiness capability of 24-36 months as required by PDD-15, some test readiness capabilities must be explicitly maintained in addition to the Stockpile Stewardship Program. Test readiness draws on SSP capabilities but in addition requires a suitable test site, a set of specialized equipment and infrastructure, and a body of specialized knowledge. The pacing item in resuming nuclear explosive testing may be regulatory rather than technical.

Recommendation 1-2: To maintain a test readiness posture of 24-36 months, NNSA should:

- Preserve the Nevada Test Site's ability to host a nuclear-explosion test;
- Support the containment capability unique to underground nuclear-explosion testing;
- Maintain seismic data necessary to meet U.S. obligations under the Threshold Test Ban Treaty should testing resume;
- Maintain the radiochemistry laboratory infrastructure and drill-back capability;[26]
- Support fast readout requirements and prompt diagnostic equipment;
- Maintain a library that includes testing methods, containment rack designs, procedures, processes; and other relevant information;
- Maintain nuclear-certifiable emplacement cranes;
- Maintain field-test neutron generators;
- Establish a process for obtaining waivers from health and environmental regulations if required, but, given the frequency with which laws change, not seek such waivers in advance.

NNSA should include all of these elements within the SSP and evaluate their status as part of the annual assessment of the fulfillment of safeguards recommended in Chapter 3 of this report.

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[24] This refers to maintaining current data required to be provided to the Verifying Party under the Protocol to the 1974 Threshold Test Ban Treaty (TTBT). Were the United States to resume testing, Russia would have inspection rights under the TTBT. Depending on the specific test, paragraph 9 of Section IV of the Protocol would require providing “a description of the geological and geophysical characteristics of the test location, which shall include: the depth of the water table; the stratigraphic column, including the lithologic description of each formation; the estimated physical parameters of the rock, including bulk density, grain density, compressional velocity, porosity, and total water content; and information on any known geophysical discontinuities in the media within a radius of 300 meters of the planned emplacement point of each explosive canister” (U.S. Department of State, 1974).

[25] The committee has noted the problems stemming from loss of institutional memory in regard to the manufacture of Fogbank (see footnote 11). This should not be repeated in other fields.

[26] The U.S Administration has asked the National Research Council to address workforce issues in the area of nuclear chemistry (NRC, 2012, forthcoming).

INTERFACE WITH DOD

Specialized technical requirements with respect to the stockpile also exist within DOD. Strategic planners must be well versed in the technical realities of weapons performance to be able to integrate knowledge of the time scales, costs and performance tradeoffs into defining weapons requirements. In addition, the DOD maintains direct technical responsibility for handling nuclear warheads and for the interface of the warheads to the control systems of the various delivery vehicles. An example of the demanding nature of this activity is the Mk-21 fuze required for the W87 warhead in the Mk-21 re-entry vehicle on the Minuteman ICBM. This fuze has a 10-year design life and thus must be replaced routinely as part of LEP activities. However, it is a custom design with rigorous performance specifications and thus is manufactured under direct Air Force control. Failure to maintain the technical knowledge base for this remanufacture has recently resulted in a problem. Addressing this problem has imposed costs and delays that could have been avoided with investment in maintaining the nuclear workforce. The knowledge and skills required for these activities are specialized, and impose the same need for care in workforce morale and sustainment as discussed above in the context of the nuclear complex (Defense Science Board, 2008).

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TECHNICAL MONITORING CAPABILITIES AND CHALLENGES

Nuclear explosions generate large amounts of energy and radioactive debris in a small fraction of a second. The rapid release of energy affects the surroundings and is propagated in ways that can be detected and separated from other phenomena. Monitoring such signals and radiological sampling are important tools in understanding the capabilities and threats presented by a State that conducts nuclear-explosion tests. The formal goals for U.S. monitoring are established by a classified presidential directive based on considerations of available monitoring technology and risks associated with detected and undetected tests. The requirements, techniques, and capabilities of the U.S. system are classified and are described only in the classified version of this report.

This chapter provides an overview of how nuclear-explosion monitoring works, with different technologies serving as elements of an overall system. U.S. national technical means (NTM) and the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) International Monitoring System (IMS) are summarized, followed by an assessment of the capabilities of monitoring technologies (seismic, radionuclide, hydroacoustic, infrasound, and satellite-based techniques). Phenomena associated with nuclear explosions, from the subsurface to outer space, are illustrated in Figure 2-1.The chapter closes with a summary of CTBTO operational capabilities, on-site inspections, and a discussion of transparency and confidence-building measures.

OVERVIEW AND *2002 REPORT* FINDINGS

To monitor for compliance with the CTBT, it is essential to be able to put potential violators at risk of detection through vigilant monitoring for nuclear explosions. The possibility of nuclear-explosion testing must be considered in four environments—underground, underwater, in the atmosphere, and in space. The Limited Test Ban Treaty of 1963 banned signatories (the United States, the United Kingdom, and the Soviet Union[1]) from nuclear-explosion testing underwater, in the atmosphere, and in space. All known nuclear-explosion tests by other countries (China, France, India, Pakistan, and the Democratic Peoples' Republic of Korea) have been underground since the last Chinese atmospheric explosion in 1980. Underground nuclear-explosion testing may be attractive to an evader because it offers the possibility of hiding details of the test and containing radioactive debris.

Each of the four environments requires different monitoring methods, each with different capabilities. All monitoring methods are based on physical signatures that are associated with nuclear explosions. These signatures are the basis for (1) concluding that an event has occurred (detection); (2) determining the location of the event (location); (3) discriminating the event from non-explosive phenomena (identification); and (4) in the case of a suspected explosion, evaluating the yield, its nuclear or non-nuclear nature, and the source of the event (characterization and attribution). A full definition of these terms is given in the glossary in Appendix K. As described in the *2002 report*, and in more detail below, there are three types of sensor networks used for monitoring purposes: U.S. NTM networks, the international network

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[1] A number of other states have since signed the LTBT and the Russian Federation is bound by the Soviet Union's treaty commitments.

defined in the CTBT, and sensor networks deployed primarily for purposes unrelated to nuclear-explosion monitoring (for example, to monitor earthquakes). By design, these networks are separate; in practice, they are often complementary. U.S. NTM provides detection, location, identification, characterization, and attribution capabilities that are primarily classified. The CTBT IMS data is available to all Member States, and the CTBTO uses it for detection and location, but the role of identification and further analysis is defined in the Treaty as one for the Member States alone. All member states' NTM, including the U.S. NTM, can make use of other sensor network data for nuclear explosion monitoring purposes.

Throughout this report IMS network capabilities are given in terms of detection thresholds. These determine the events the CTBTO reports on and determine the data available to the States Parties, including data such as IMS auxiliary stations, which are retrieved upon formation of an event. These thresholds define the IMS data available for States Parties to use in their role of event identification, characterization and attribution. Differences between detection and identification threshold are discussed on pages 48-49, and as noted, they can be the same when calibrated regional discriminants are used.

Figure 2-1 shows the various regions of nuclear explosion phenomenology—subsurface, atmosphere (low altitude), transition (high altitude), and space (monitored by the satellite nuclear detonation detection system).

Nuclear Detonation Phenomena

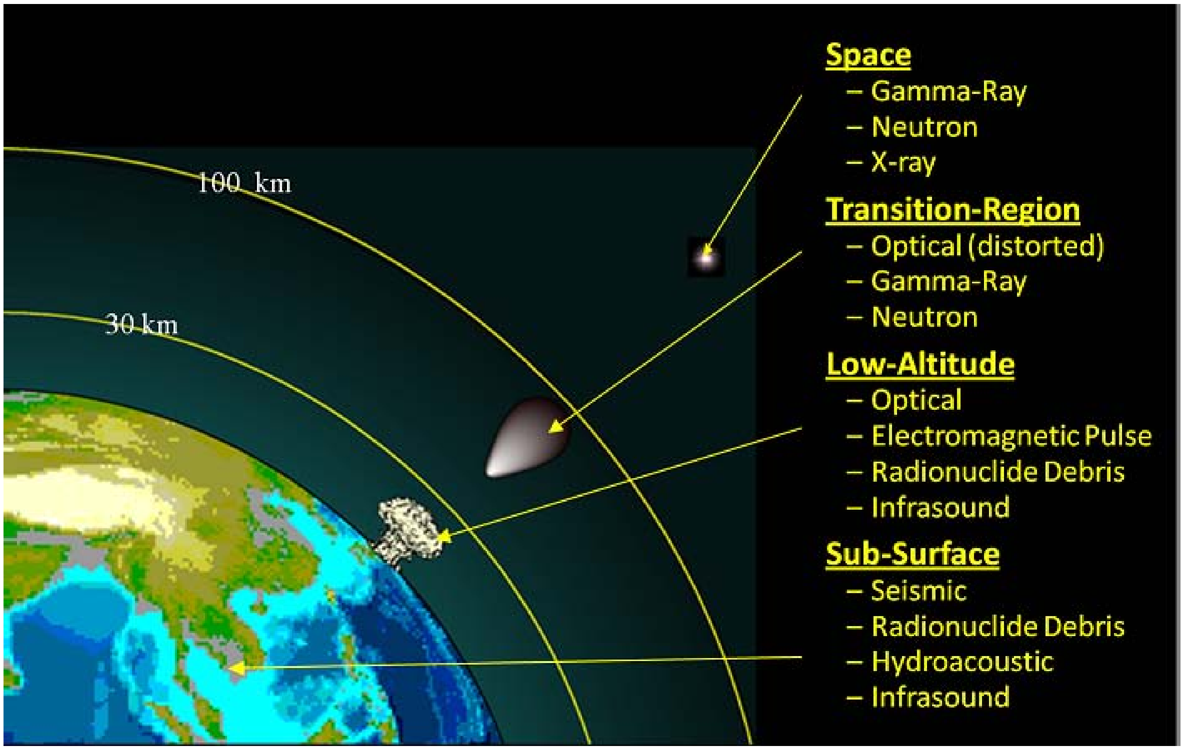

FIGURE 2-1: Phenomenology of nuclear explosions, from the subsurface to outer space. SOURCE: U.S. DOE, 2004

Table 2-1 summarizes the signals that originate from nuclear explosions in different media, how they propagate through the environment, and what technologies are used to detect the signals today.

TABLE 2-1: Phenomena Associated with Nuclear Explosions, and Technologies Used for Monitoring Them.

Phenomena	Primary Monitoring Environments	Propagation	Technology Used
Seismic Waves	Underground, underwater	Through the Earth and water	Seismometers
Radionuclides—Particulate and Gases	Atmospheric, underground, underwater and space	Through air; through water; through rock fractures; through space (trapped in the Earth's magnetic field)	Ground-based and airborne collectors; satellite-based detectors
Hydroacoustic Waves	Underwater	Through water	Hydrophones—T-phase seismic stations
Infrasound Waves	Atmospheric	Through air	Infrasound detectors
Electromagnetic Pulse (EMP)[2]	Atmospheric	Through air and space	Satellites—EMP burst detectors*
Optical Flash	Atmospheric, space	Through air and space	Satellites—Optical flash detectors*
Nuclear Radiation	Space	Through space	Satellites—Radiation detectors*

* Not included in the IMS but available through NTM.
SOURCE: Committee

In cases where multiple detection technologies complement one another for the same event, the data from these disparate detection technologies can be brought together or "fused" in order to improve the capabilities for detection, location, and identification. It is this data fusion that determines the ultimate monitoring capabilities relevant to the CTBT. Based on developments over the past decade, each of the technologies that can be used to monitor compliance with the CTBT is reviewed below and updated from the *2002 Report*. For each technology, the committee considers U.S. NTM, the IMS, and other capabilities. Augmenting the technologies summarized in Table 2-1 is information derived from confidence-building measures (CBMs) and on-site inspections (OSI), both of which are also described in this chapter.

The *2002 Report* assessed the capabilities proposed under the CTBTO IMS and stated that, when fully implemented, the IMS would detect and identify explosions with a yield of at least one kiloton (kt) with high confidence *in all environments*, assuming no efforts at evasion. For underground explosions, it said that a yield of 10-100 tons would be detectable, although explosions of less than a few kilotons might require an on-site inspection to confirm the explosions as nuclear. Tests above 500-1,000 tons for atmospheric explosions could be characterized as nuclear, and nuclear-explosion tests as low as one ton would be detected if

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[2] EMP is an intense pulse of electromagnetic radiation resulting from electric currents produced by energetic radiation (neutrons, gamma rays and x-rays) from a nuclear explosion. High-altitude EMP (HEMP) observed at the ground from a space nuclear explosion has a very fast component (E1) produced by the gamma rays interacting with the atmosphere and a slow component (E3) caused by the expansion of the debris "bubble" in the Earth's magnetic field.

they were conducted underwater. Technical advances since the *2002 Report* are discussed in sections dealing with specific monitoring technologies later in this chapter.

Several proposed evasion scenarios were also considered in the *2002 Report,* which concluded that the only plausible techniques were cavity decoupling (a potential method for reducing the size of the seismic signal created by an explosion by muffling the explosion in a large underground cavity) and mine masking (concealing a nuclear explosion by conducting a nuclear test in a region that has frequent, large chemical explosions associated with mining operations). The report also concluded that either of these techniques would be difficult to employ successfully and that they would have a significant chance of being detected by the IMS for all but very low yields. Evasion techniques are discussed further in Chapter 4 and Appendix E.

U.S. NATIONAL TECHNICAL MEANS

The United States developed and maintained the capacity to monitor nuclear-explosion tests long before any test limitation treaties existed. Today that work is carried out by the Air Force Technical Applications Center (AFTAC). AFTAC's mission is "the detection of nuclear detonations…anywhere in the world: below ground, in water, surface blasts, free-air, and in space." It operates and maintains the U.S. Atomic Energy Detection System (USAEDS), which is used to monitor treaty compliance. AFTAC collects and analyzes data from a variety of sources and is home to the U.S. National Data Center (U.S. NDC), which engages with the IMS and the International Data Centre (IDC) of the CTBTO in the exchange of data and data products as specified in the text and protocols of the CTBT. Other government agencies, notably NNSA and the DOE national laboratories, carry out research on new and improved technologies to monitor nuclear explosions and AFTAC draws on the expertise of scientists in the DOD and DOE laboratories, the U.S. Geological Survey, U.S. academic institutions, and private contractors. New technologies are transferred to and beta-tested by AFTAC operators.[3] In contrast with the CTBTO monitoring system, whose monitoring networks, technologies, and station placements are defined by the Treaty, U.S. national technical means may take advantage of technologies not part of the IMS (for example, space-based monitoring) and may focus its monitoring efforts on areas of particular interest to the United States.

NTM give the United States significant additional information beyond what is available to other countries that do not have a robust NTM program. U.S. NTM can focus on monitoring countries of concern to the U.S. The United States global monitoring capabilities are generally better than those of the CTBTO because they can go beyond data available to the CTBTO with classified capabilities. However, the inclusion of classified means and data limits the extent to which analyses and even results may be shared and used openly. Drawing on all available assets is important because there are CTBTO installations in locations where the United States cannot readily deploy stations, as well as thousands of stations that operate independently of U.S. NTM and the IMS.

Finding 2-1: U.S. National Technical Means provide monitoring capability that is superior to that of the CTBTO, but the use of U.S. NTM for diplomatic purposes may be constrained due to its largely classified nature.

Finding 2-2: The International Monitoring System provides valuable data to the United States, both as an augmentation to the U.S. NTM and as a common baseline for

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[3] See: *http://www.tt.aftac.gov/WRT/U.S.IMS/Index.html*.

international assessment and discussion of potential violations when the United States does not wish to share NTM data.

THE CTBTO INTERNATIONAL MONITORING SYSTEM

The CTBTO is based in Vienna, Austria. Its key elements are (1) the IMS, which generates data from its radionuclide, seismic, infrasound, and hydroacoustic networks, and (2) the International Data Centre, which collects and processes the IMS data. Because the threat of data manipulation or denial using cyber attacks is a possibility, the IDC takes precautions to reduce this risk, including the use of a dedicated global communication infrastructure, data authentication and encryption, station intrusion-detection devices, and regular data back-up.

In addition, if the Treaty enters into force, there will be the possibility for conducting on-site inspections (OSI). IMS data are transmitted in near-real time to the CTBTO and to those national data centers (NDC) that request them. Figures 2-2 through 2-6 locate and give the status of the more than 300 stations (whether certified, installed, under construction, or not yet started) of the IMS (the 50-station primary seismic network, the 120-station auxiliary seismic network,[4] and 80-, 11-, and 60-station networks for radionuclide, hydroacoustic, and infrasound technologies, respectively) as of mid-2010. The IMS monitoring station locations were determined to maximize global coverage without focusing on any particular countries.[5]

A major advance in the last 10 years is that the number of certified[6] IMS stations grew from three in October 2000 to 264 in February of 2011, with an additional 17 stations installed and undergoing evaluation. By February of 2011, about 83 percent of the full network was implemented (certified stations plus those undergoing testing) and will approach 90 percent by the end of 2011. Different stations address different components of the IMS mission, as shown in Figures 2-2 through 2-6.

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[4] Many of the primary stations, which operate continuously for the IMS, are seismic arrays that enable measurement of the direction to an event of interest and that enhance capability to detect small signals and features, such as the surface-reflected waves that help determine the depth of the event. The auxiliary seismic network records continuously but currently its data are used only when deemed necessary to augment analysis of an event that has already been detected by the primary network

[5] In assessing the capabilities of the IMS, it is important to understand that the treaty specifies that event identification, characterization, and the attribution of a nuclear explosion to a particular country are the responsibility of the member states, not the CTBTO. Thus the CTBTO provides data on all detected events, as well as subsets for which events characterized (with high confidence) as earthquake-like have been screened out, but the United States does not rely on the CTBTO for screening to decide whether a particular event was a nuclear explosion. CTBTO is *not* responsible for identifying and characterizing seismic events as nuclear explosions, earthquakes, or chemical explosions; nor does it deal with assessing evasive testing such as decoupling (see Chapter 4).

[6] A *certified station* in the context of the CTBT refers to a station that has been judged to substantially meet a set of technical and operational requirements specified in the operational manuals. Certification is essentially the last step in the process of establishing a station before data from that station is trusted.

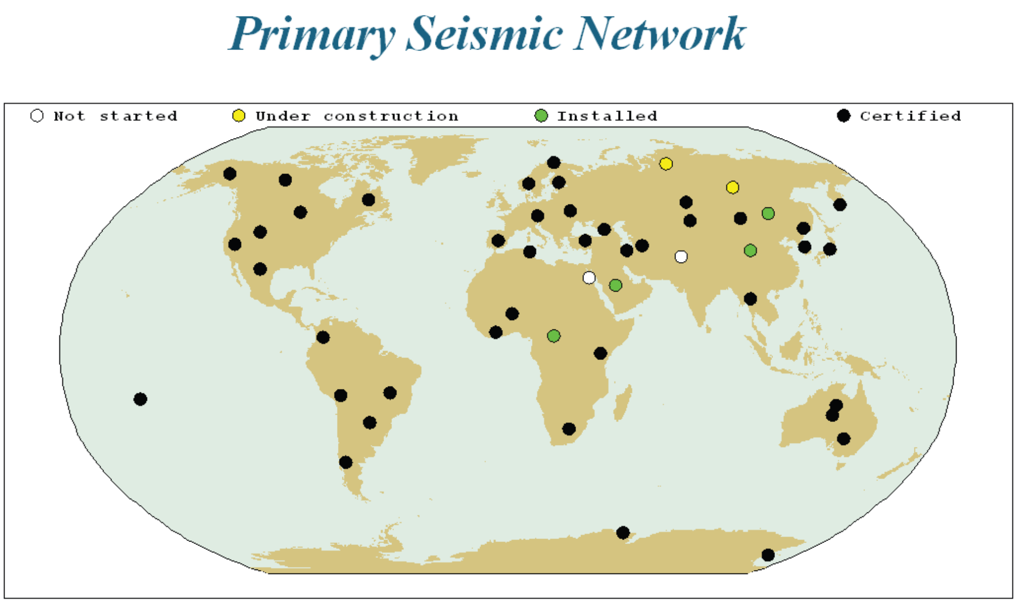

FIGURE 2-2: Location and status of 49 stations of the IMS Primary Network, as of mid-2010 (the location of an additional station was undecided). Certification is the final step in preparing to send data in real time via satellite to Vienna, and 42 stations are shown here as having passed this stage. SOURCE: Modified from CTBTO

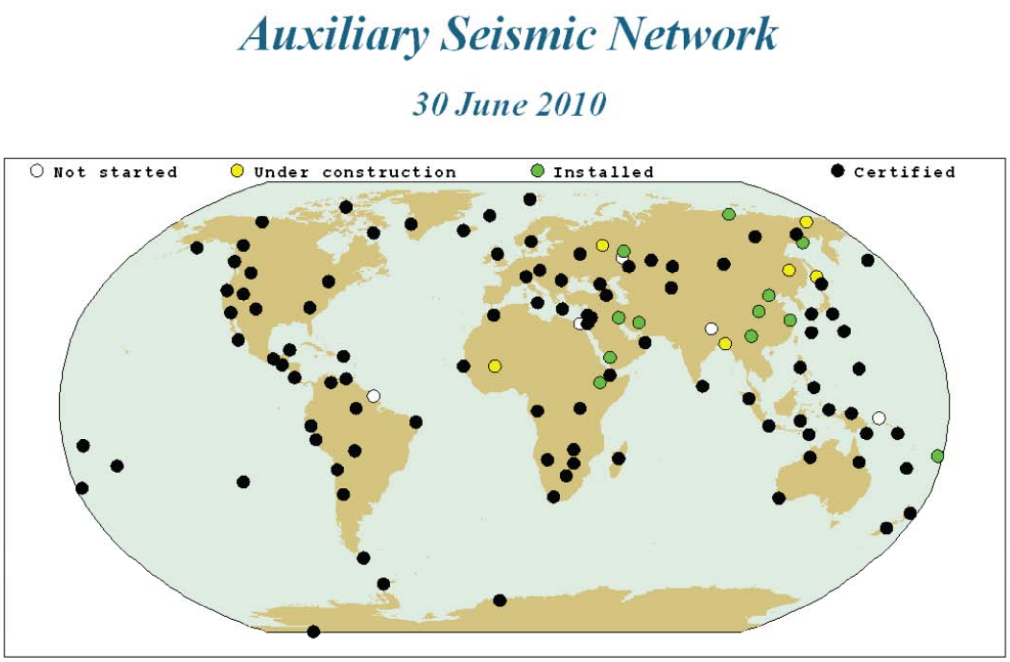

FIGURE 2-3: Location and status of 120 stations of the IMS Auxiliary Network, as of mid-2010. Auxiliary stations are supported by the hosting state and not the CTBTO. SOURCE: Modified from CTBTO

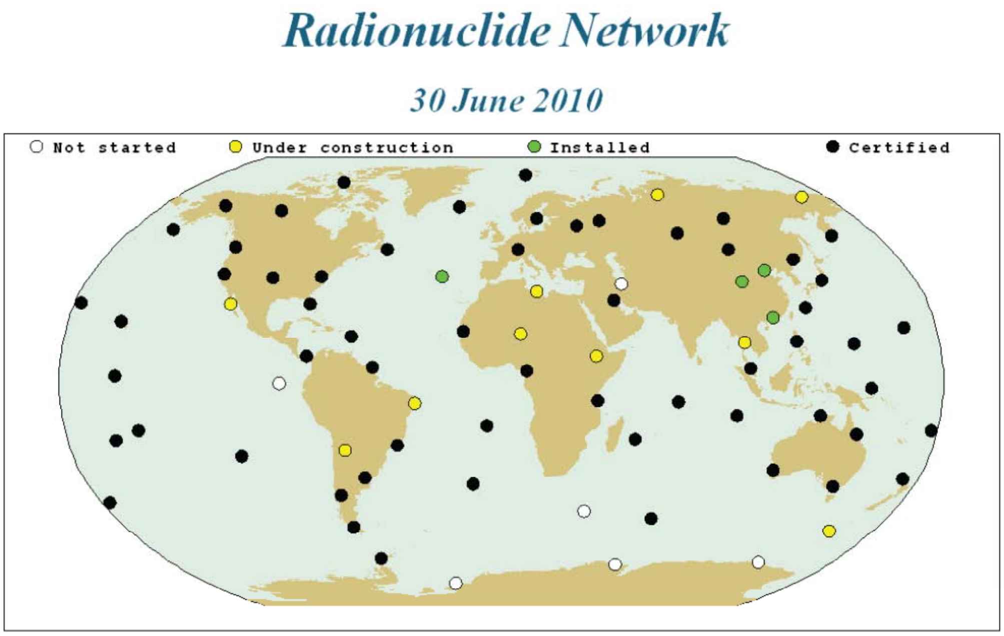

FIGURE 2-4: Location and status of 80 stations of the IMS Radionuclide Network, as of mid-2010. All of these stations will monitor for particulates, with 40 of the stations to monitor for xenon (gas) isotopes that are diagnostic of nuclear explosions. As of February 2011, 26 of these noble-gas stations were transmitting data to the IDC in Vienna. SOURCE: Modified from CTBTO

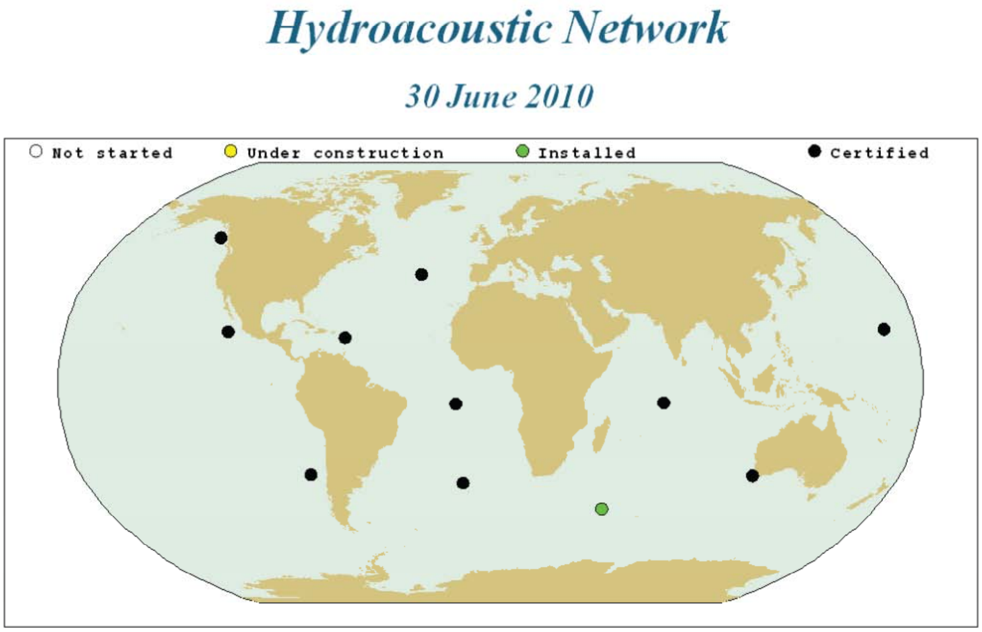

FIGURE 2-5: Location and status of 11 stations of the IMS Hydroacoustic Network, as of mid-2010, when damage at two stations was under review for repairs (Crozet Island, shown in green; and a station off-shore from Chile which was destroyed by a tsunami early in 2010). SOURCE: Modified from CTBTO

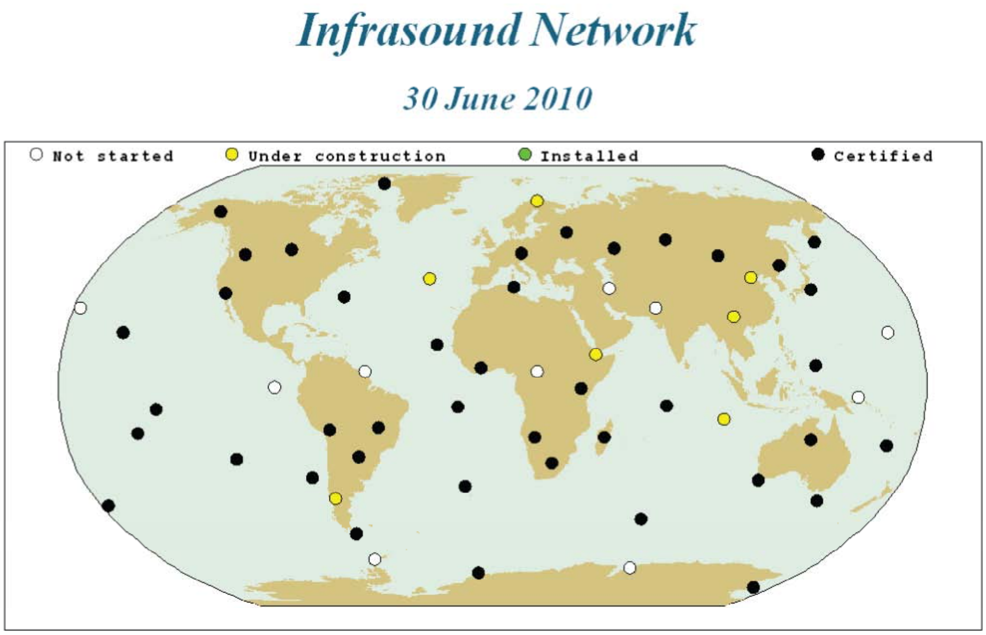

FIGURE 2-6: Location and status of 60 stations of the IMS Infrasound Network, as of mid-2010. SOURCE: Modified from CTBTO

The Treaty defines mechanisms for non-IMS data to be used for the purposes of "consultation and clarification" and for consideration of an OSI request. Member States may also request particular technical analyses from the CTBTO that can incorporate non-IMS data, resulting in a special product that is attributed to the requesting State but made available to all Member States. Finally, States may do their own processing, using any data they wish, including NTM, and present their results to other Member States for Treaty purposes.

One of the CTBTO's main products is the IDC Reviewed Event Bulletin (REB) for waveform-technology-based events (the waveform-based REB merges data from seismic, hydroacoustic, and infrasound stations). The REB, along with other bulletins, keeps States informed of events detected by the IMS. The IDC's event identification role is that of "Assisting individual States Parties...with expert technical advice...in order to help the State Party concerned to identify the source of specific events." Even though the monitoring capability of the United States through its NTM is generally superior to that of the IMS, the data collected by the CTBTO is a trusted, valuable and reliable source of relevant information for U.S. monitoring purposes. USAEDS and IMS share 22 seismic stations and 3 hydroacoustic stations.

The raw data from the IMS is both protected and authenticated in multiple ways to decrease the likelihood that data collected and transmitted could be tampered with. In addition, there are multiple methods used to back up the IMS data so that accidental or intentional erasure is also very unlikely. Great efforts have been made to provide data that is both well characterized and secure. Electronic data encryption, intrusion detection, and power backups protect data at the source; data is then transmitted through the Global Communications Infrastructure (GCI), a dedicated communications channel designed and enabled specifically for the CTBT.[7] In addition, any state party is free to keep its own back-up of IMS data and/or IDC products if it chooses to do so.

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[7] These IMS stations have a satellite link to the IDC in Vienna. Some send data continuously (e.g., the primary seismic network). Others send data only on request or at regular intervals.

The CTBTO plays an important role for the U.S. by providing a common baseline of data to the world scientific community, as well as providing data from areas that the United States has previously had difficulty accessing. CTBTO analysis, software, and training/outreach activities help to create and maintain a level of technical capability and common interpretation of data. The CTBT provides additional verification tools beyond the IMS through an on-site inspection mechanism and means to address events of concern through consultation and clarification with Member States. The IDC event bulletins provide screened information to help Member States make their own compliance decisions. A common misconception is that the United States and its allies will rely solely on the IMS for verification of compliance with the CTBT. "The treaty mandates that each State Party maintain a National Authority to serve as the national focal point for liaison with the CTBTO and with other signatories" (NRC, 2002, pp. 38).

Recommendation 2-1: The United States should support both the completion of the IMS and its operations, training, and maintenance, whether or not the CTBT enters into force. If the CTBT were to enter into force, the resulting expertise would also aid in gaining consensus on compliance issues, including, for example, authorizing an on-site inspection.

OTHER CAPABILITIES

There are instrument networks that have other primary uses but that have value for detection of nuclear explosions. Examples are the numerous regional networks of seismometers used for earthquake detection and the international tsunami warning system. Other networks, such as those that monitor radionuclides from nuclear power plants, could also provide potentially relevant data for analysis in the event of a suspected atmospheric detonation.

MONITORING TECHNOLOGIES[8]

Seismic

Seismology is the most effective technology for monitoring underground nuclear-explosion testing, the one environment that was not precluded from nuclear-explosion testing by the Limited Test Ban Treaty of 1963. Seismic monitoring for nuclear explosions is complicated by the great variety and number of earthquakes, chemical explosions, and other non-nuclear phenomena generating seismic signals every day. More than 600 earthquakes per day are regularly documented in an international summary report, and mining operations use several million tons of chemical explosives each year. Programs to sort out and identify signals from underground nuclear explosions in the midst of signals from these other phenomena have made great progress since they commenced in the 1950s, with notable improvements in the past ten years.

Changes since the *2002 Report*

Substantial improvements in the U.S. and international ability to monitor underground nuclear-explosion testing have been made since the *2002 Report* in three areas:

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[8] In this report, we use the term *monitoring* to refer to all aspects of detection and characterization of an event (e.g., nuclear vs. non-nuclear, geolocation, yield estimates, etc.).

1. Verification research and development efforts have resulted in the implementation of new regional distance (<1,600 km/1,000 miles) seismic methods to detect, locate and identify events.
2. Many more high-quality, broader bandwidth, digital seismic stations and arrays have been deployed globally and many of these stations transmit data in near-real time.
3. Increases in computing power and affordable, online, digital storage of waveforms on the terabyte scale have led to improvements in all aspects of seismic monitoring.

Two important events since the *2002 Report* were the announced underground nuclear-explosion tests by North Korea in 2006 and 2009. These events were readily detected, located, and identified as described in Box 2-3,[9] demonstrating how the technological advances have improved both U.S. NTM and CTBTO IMS monitoring. Figure 2-7 indicates the extent of improvements in seismic monitoring achieved over the last 20 years.

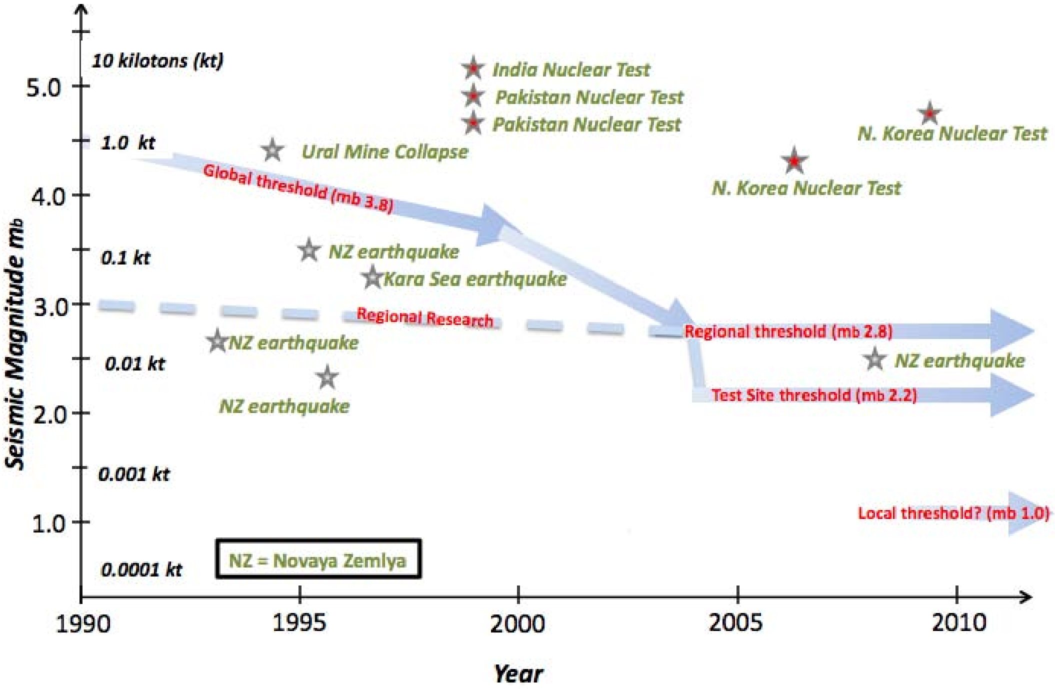

FIGURE 2-7: Improvement in seismic monitoring over the last 20 years. Threshold values indicate statistically significant confidence of detection. Note that yield and seismic magnitude scales are logarithmic; each unit of improvement is a factor of ten. Seismic sensitivity to nuclear explosions has improved significantly due to increased deployment of seismometers and improved data analysis. For locations of interest, this allows regional monitoring at distances less than about 1,600 km (1,000 miles), which has a much lower threshold (~ 20 tons or 0.020 kilotons explosive yield) than does global monitoring (~ 200 tons or 0.20 kilotons) recorded at distances typically greater than 2,000 miles. Monitoring at test sites (e.g., through transparency

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[9] See, for example, the U.S. Director of National Intelligence (DNI) statements in Box 2-3 and the CTBTO web site pages on these events. Examples of regional seismic techniques for these events are given in Appendix D.

measures) can bring the sensitivity down to about 5 tons, or 0.005 kilotons.[10] SOURCE: Seismology Subcommittee

Seismic Signals

Seismic signals can propagate as "body waves" through the solid body of the Earth, including its deep interior, or as "surface waves," which travel along the Earth's surface (analogous to the ripples on the surface of a pond). Body waves can further be divided into P-waves (the P standing for "primary"—these waves travel the fastest of all seismic waves and hence are the first to arrive) and S-waves (S standing for "secondary"—their speed is about 60 percent that of P-waves). P-waves (which entail a longitudinal motion pushing and pulling in the same direction in which they travel) are efficiently excited by explosions, whereas typical earthquakes are efficient producers of S-waves (which entail a transverse motion, or shearing, perpendicular to the direction in which they travel) and surface waves.

Seismic signals are traditionally grouped into categories of "teleseismic" or "regional" depending upon the distance at which they are observed.[11] Teleseismic waves do not greatly diminish with distance in the range from about 2,500 to 9,000 km (1,563-5,625 mi), so they are suited to monitoring a large country from stations deployed outside that country's borders. Teleseismic waves were the basis of most nuclear-explosion test monitoring prior to the 1990s. For sub-kiloton explosions, teleseismic monitoring can often still help with event detections but is likely to be inadequate for event identification and therefore monitoring benefits from regional-distance signals.

Regional waves, though often useful because they can carry more information than teleseismic waves, are often harder to interpret because they exhibit greater variability. The characteristics of these waves, and the ways they vary for stable and tectonic regions as well as for continents and oceans, have been extensively researched, beginning in the late 1980s. Under the Threshold Test Ban Treaty, the primary monitoring concern was nuclear-explosion testing over 150 kt. This monitoring requirement could be easily handled at teleseismic distances; under the CTBT, however, the challenge is to identify and characterize all nuclear-explosion tests, regardless of size. Stations at closer distances can see smaller-sized events, but the waves travel through the most complex part of the Earth—the crust and upper mantle—which can distort the seismic signals. While research into regional seismic methods was underway in the 1990's, research products were just beginning to be applied to real-time monitoring. Today, many regional monitoring methods have proven viable for detection/association, location, identification and event characterization in real time. For many continental areas, the use of regional data has improved monitoring sensitivity by as much as a factor of ten compared to purely teleseismic methods. As more stations and arrays are deployed

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[10] Approximate fully-coupled yields are shown in Figure 2-7, as described in the *2002 Report* (NRC, 2002, p. 41), with global monitoring sensitive down to magnitudes m_b = 3.8 (corresponding to fully-coupled yields of about 135-250 tons, depending on geology, shown here as 200 tons) and regional monitoring sensitive down to m_b = 2.8 (fully coupled yields of about 6-25 tons, depending on geology, shown here as 20 tons). Sensitivity for monitoring at test sites goes down to m_b = 2.2, or ~ 5 tons fully coupled yield. Yields for Regional and Test Site thresholds refer to unclassified capabilities for monitoring countries of concern to the U.S. for well-coupled explosions. The mention of a *local threshold*, lower right in figure, refers to the future possibility of bilateral monitoring agreements, distinctly separate from the CTBT. The magnitude estimates listed on this figure are from the IDC and other public sources. See Figure D-1 and additional detail in Appendix D.

[11] *Regional* and *teleseismic* refer to event-station distances of less than 1,600 km (1,000 miles) and greater than 1,600 km, respectively.

and more signals are transferred in near-real time, these current and newly emerging techniques will continue to lower monitoring thresholds.

Seismic Event Detection, Association, and Location

A high-quality station may be expected to detect tens or even hundreds of seismic signals per day, many of them from nearby or "local" sources. With many different events each day, seismic waves from different events may be superimposed at any particular station. The work of association is to identify the sets of signals, from different stations, which all originate from the same seismic event such as an earthquake or an explosion.

A refined estimate of the location of the seismic source is obtained by iterating to find a point in the Earth (latitude, longitude, depth), and an origin time, from which the seismic waves arrived at the set of observed times at different stations. The accuracy of seismic event location depends on measurement and model errors. These errors lead to seismic event location uncertainty, usually quantified as an area, such as an ellipse (within which there is a specified degree of confidence that the event must lie), rather than as a point. Accurate seismic locations are important for attribution, to help with identification (for example, if the event is definitely deeper than, say, 10 km [6.2 miles], it is unlikely to be an explosion) and because the CTBT limits an OSI area to no larger than 1,000 km^2 (for example a circle with a radius of about 18 km, or 11 miles).

Location measurement error is related to the uncertainty in timing the arrival of the seismic signals, which can vary with event size and distance. Larger events with simple paths through deep Earth can be timed more accurately than those with weak signals or complex paths. Increases in computing power and the online storage of large amounts of seismic

BOX 2-1 Estimation of the Yields of Underground Nuclear Explosions from Seismic Magnitudes

To assess the size of a detected event in terms of nuclear yield, yield typically must be derived from seismic magnitude. A single relationship between magnitude and yield does not exist. This is because explosions of a given yield generate different amplitudes of seismic waves (and hence different magnitudes) depending upon 1) the efficiency of seismic wave propagation from source to recording stations, 2) the rock type at the source, 3) depth of the explosion, and 4) whether the explosion is well coupled or decoupled. Here we examine the first three factors in the calculation of yield from seismic measurements for well-coupled explosions in either hard rock or below the water table (See Appendix E for details about decoupling).

Formulas relating the body-wave magnitude, m_b, to the yield, Y, based on data from past underground nuclear explosions are of the form

$$m_b = A + B \log(Y),$$

where A and B are constants that depend on features 1–4.

Most past tests of yield greater than about 1 kiloton were detonated at greater depths as yield was increased so as to ensure containment. Their data are well fit by B = 0.75 (Murphy, 1996). Nuclear explosions at eastern Kazakhstan, Lop Nor China and northern India are characterized by efficient propagation of P waves such that

$$m_b = 4.45 + 0.75 \log(Y),$$

where Y is in kilotons. Explosions in Nevada are characterized by poorer propagation of P waves such that the constant A is smaller

$$m_b = 4.05 + 0.75 \log(Y).$$

Hence, for a given m_b the yields calculated for explosions at Lop Nor are smaller than those at the Nevada Test Site. Propagation of P waves from th main Russian test site at Novaya Zemlya is somewhat less efficient than that from eastern Kazakhstan, resulting in A = 4.30. Nuclear explosions in hard rock, in salt or below the water table are characterized by magnitudes that differ very little ($\pm$ 0.1 m_b units) once corrections are applied for differences in the propagation of P waves (Murphy, 1996). Explosions in water and saturated clay produce seismic waves that are substantially larger (Murphy, 1996). For explosions of varying yield *at the same depth* B =1.0. For explosions with very small magnitudes, i.e. those less than $m_b = 4$, we calculate yields using B = 1.0 because such small nuclear tests are not likely to be conducted at the depths that B = 0.75 would imply. For a given m_b, use of B = 1.0 leads to more conservative (larger) estimates of yield for very small explosions than does B = 0.75.

data have allowed much greater use of signal processing techniques that greatly reduce measurement errors. This is an area for which there are opportunities for substantial future improvement.

Location error also arises from inadequate models of the geologic variability in the Earth, which is not fully known. Seismic waves travel at different speeds through different rock types. If this is not fully accounted for in the Earth models used for seismic location, the event area will not be centered on the true location. Regional wave signals, which travel through the most complex part of the Earth, can be misinterpreted more easily than teleseismic wave signals if not properly calibrated. Since the *2002 Report* there has been significant progress in performing continental scale calibrations. These calibrations have been done using well-located reference events to derive travel time corrections for all future nearby events. Most recently, increases in computing power, data storage, and regional R&D have resulted in new models for Eurasia that allow accurate location of events well away from reference events. These models are derived using large-scale tomography, similar to medical imaging, but where the regional seismic waves from many earthquakes are used to image the Earth. They reduce the regional model errors to be of similar size to teleseismic ones allowing easy mixing of teleseismic and regional data and can achieve location accuracies of 1,000 km^2 (390 mi^2) area or better for small events (Myers et al., 2010). As our knowledge of Earth structure improves, location model error can be expected to decrease.

Seismic Event Magnitude and Identification

Event identification is done by comparing the amplitude characteristics of different types of seismic waves. For teleseismic waves, the relative size of body waves and surface waves is an effective discriminant. As noted in Box 2-1 the strength of a seismic source as determined from the amplitude of its body waves is conventionally reported as the body wave magnitude, symbolized as m_b.[12] Correspondingly, the size of surface waves is reported as the surface wave magnitude, M_s. Shallow earthquakes have a larger relative surface-wave magnitude than do underground nuclear explosions having the same body-wave magnitude. For small events, it can become difficult to measure the surface-wave magnitude above the background noise. However, new regional identification methods have proven very effective at identifying small explosions, extending seismic identification capabilities (as an explosion) down to the smallest events.

During the past decade, many new research products were implemented into the routine operational systems that continue today. Regional seismic waves travel through the Earth's crust and uppermost mantle (the top few tens of kilometers of the Earth's interior) at high frequencies. The high frequencies enable new methods for distinguishing the seismic signals produced from a small underground explosion as compared with naturally occurring earthquakes. In Appendix D, examples are shown of how regional high-frequency signals can be used to identify explosions for broad regions of the world and for explosions as small as a few tons.

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[12] The signal amplitude is measured at each station with a detectable *P*-wave, a correction for the effect of the distance between source and station and for the source depth is made, and the magnitudes obtained for each station are averaged to obtain the network magnitude. Details can differ in the way that different institutions assign m_b. Noise levels at stations that do not report a detection can be incorporated into the process to obtain more accurate magnitudes of small events (e.g., maximum likelihood methods).

Seismic Monitoring in Tectonically Active Regions

Magnitude scales in seismology are logarithmic, so signal amplitudes are ten times smaller for a source with m_b = 3, as compared with one with m_b = 4. On average, about 21 seismic events worldwide above magnitude 4.0 occur daily, and the number goes up by a factor of about 10 for each drop of one unit in magnitude (say, from 21 to 210 events a day for a drop in magnitude from 4.0 to 3.0).[13] The majority of the small earthquakes each day occur in tectonically active regions where the Earth is undergoing active deformation (e.g., California, Japan, Iran, or Italy). Such areas pose challenges both because of the number of events that need to be correctly processed and because the Earth's complex structure distorts and attenuates the seismic waves. On the other hand, areas with large numbers of seismic events generate a great deal of data that can be used to calibrate them.

Initially, the Middle East presented a serious example of the challenges of monitoring a seismically active area. The overall burden to identify seismic events as earthquakes in this region (and thus not of concern under the CTBT) was significant. Monitoring seismic activity in the Middle East became the focus of much research and development effort, which used the large number of earthquakes to calibrate the region. Identification of explosions in the Middle East can now be accomplished by the usual methods once the complex Earth structure in the region is taken into account.

Seismic Monitoring Sensitivity

The relationship between explosive yield and event magnitudes depends on the geology in the region of the event and the strength of coupling to surrounding media. The m_b-yield relations applicable to Semipalatinsk (a former Soviet test site in Kazakhstan) and Nevada Test Site (NTS) explosions represent the lower and upper bounds for non-evasively-tested underground explosions in good coupling media. Comparison of the resulting Semipalatinsk and NTS detection thresholds indicates that the latter are about a factor of 4 larger in terms of yield than the former (see Box 2-1). The NTS m_b-Y assessment will be valid for seismically attenuating regions (e.g., Iran), whereas the Semipalatinsk assessment will be valid for regions of more efficient wave propagation (e.g., Lop Nor in China and North Korea).

Detection and identification sensitivities are governed by having an adequate number of sensors to record the higher frequency regional signals.[14] Accurate location and identification will depend upon whether a sustained calibration effort has been undertaken.

In teleseismic monitoring, signal levels needed for event identification are often given as higher than the levels for event detection. That is, signals need to be available at higher signal-to-noise ratios for identification than for detection and location. However, with regional monitoring, small explosion (<~1 kt) identification may be done at one or two of the closest stations. In cases where P- and S-waves propagate efficiently, this leads to an identification threshold at or below the three-or-more-station detection/location threshold. In active tectonic areas such as the Middle East, however, the S-waves can be more strongly attenuated than P-waves, leading to a higher threshold for identification than for detection/location when high-

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[13] This number is based on the CTBTO's IDC defined maximum likelihood m_b scale, which was set up for explosions and which takes into account stations where the signal is below the noise level (e.g., Ringdal, 1986). For comparison, the U.S. Geological Survey m_b scale is similar to that of the IDC for explosions, but for earthquakes (for complex reasons) m_b(USGS) ~ m_b(IDC) + 0.45 (see Granville et al., 2005) leading to about 35 events per day above m_b = 4. See: *http://earthquake.usgs.gov/earthquakes/eqarchives/year/eqstats.php*.

[14] Throughout this report (unless otherwise qualified), by "detection threshold" we mean detection at 90 percent confidence and at enough stations to provide a location estimate.

frequency P/S identification methods are used. On average, in many regions of the world, the regional detection/location and identification thresholds are expected to be similar, but more work is needed to quantify the identification threshold in regions of strong S-wave attenuation. Examples of good identification capability, albeit with a regional network that is sparse, are given in Appendix D.

In the following sections, seismic maps based on both empirical data and computer simulations are used to estimate the minimum detectable monitoring levels for both the U.S. NTM and CTBT IMS networks in terms of seismic magnitude m_b at a fixed confidence level (e.g., 90 percent).

Finding 2-3: Independent of the CTBT, the national security interests of the United States and its allies require the seismic monitoring of foreign nuclear-explosion tests.

Finding 2-4: Technical capabilities for seismic monitoring have improved substantially in the past decade, allowing much more sensitive detection, identification, and location of nuclear events. More work is needed to better quantify regional monitoring identification thresholds, particularly in regions where seismic waves are strongly attenuated.

U.S. Seismic NTM

Over several decades the United States has built a sophisticated national monitoring system to detect, identify, and characterize nuclear-explosion tests. From 1999 to 2009, this system has improved significantly.

Recommendation 2-2: AFTAC should study the extent to which detection thresholds could be improved by making fuller use of the authenticated data from the IMS as well as targeted use of calibrated non-IMS seismic stations to help characterize special events of high concern.

Recommendation 2-3: To meet its national security needs, the United States should continue to enhance and sustain its NTM seismic monitoring capabilities.

IMS Seismic Monitoring

One of the major advances of the last 10 years is that 84 percent of the planned primary seismic stations are operating and certified for data quality (including calibration) and integrity (with respect to tampering and data authenticity), as well as 83 percent of the planned auxiliary stations (as of February 2011). Many of the primary stations are seismic arrays, which, unlike single stations, have the capability to determine the azimuth from which a seismic wave arrived and the distance to its source. Many arrays are very good at detecting small events and seismic waves following the P-wave, which allow an event's depth to be determined. Several of the IMS seismic stations and arrays, such as the array in Niger in west-central Africa, are among the most sensitive in the world.

Figure 2-8 shows the detection capability of the IMS seismic network as of 2007.

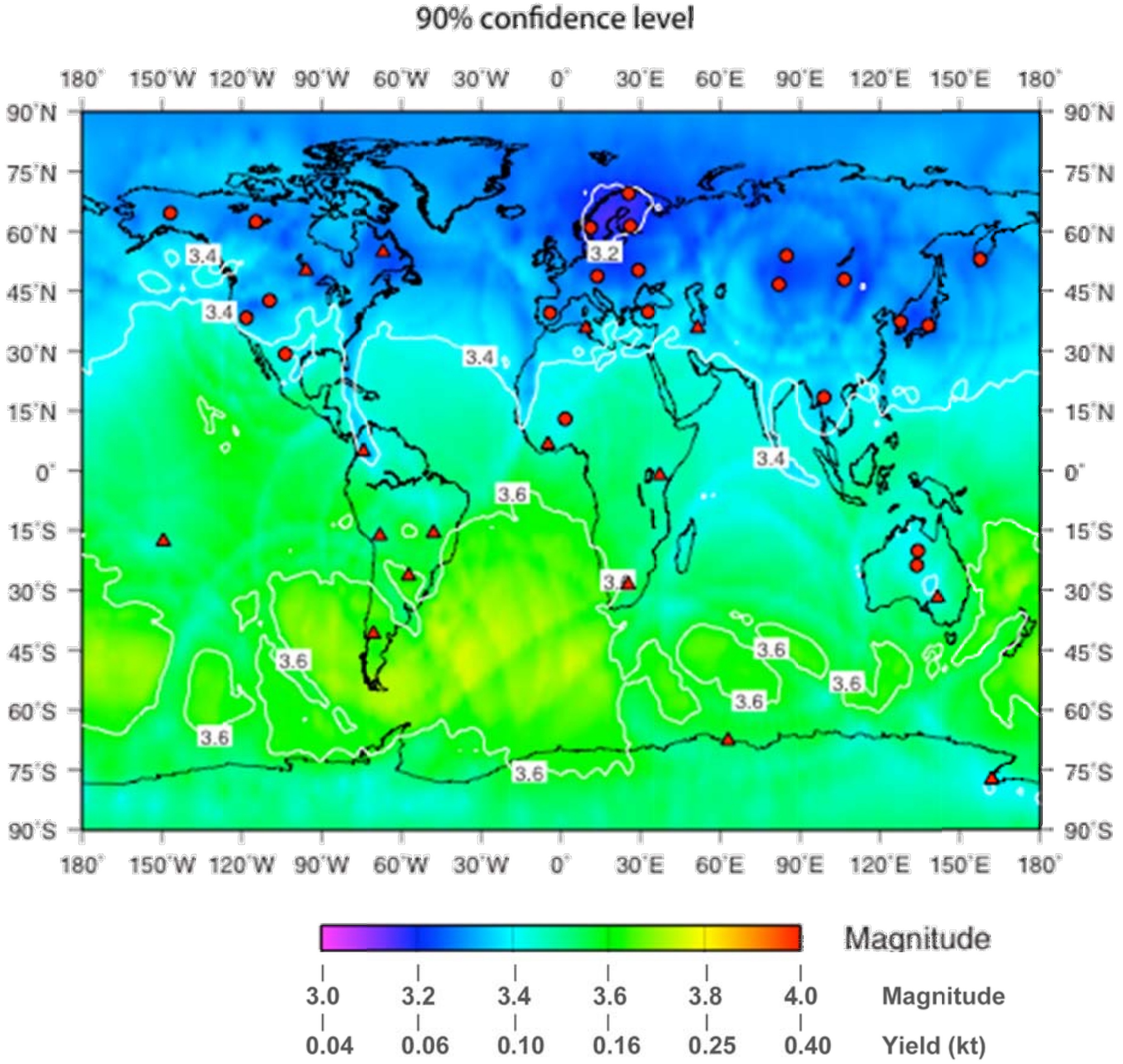

FIGURE 2-8: Detection Capability of the IMS Primary Seismic Network in late 2007, with 38 stations sending data to the IDC. Contours, indicate the magnitude of the smallest seismic event that would be detected with a 90 percent probability at three or more stations; that is, at enough stations to enable a location estimate. Red circles are seismic arrays, and triangles are single seismic stations. Completion of this network (to 50 stations) would reduce these magnitudes by about 0.1 or 0.2 units for Asia, much of Africa, and the Indian Ocean. The resulting capability, based extensively on operational experience, is quite similar to that described in the *2002 Report*, which was a calculation of how well the then far-from-complete primary network would eventually operate (The magnitude yield relationship comes from Box 2-1). SOURCE: Capability map prepared by Tormod Kværna and Frode Ringdal, NORSAR

The detection capability of approximately magnitude m_b = 4.0 or ~1 kiloton (kt) for well-coupled nuclear explosions is being significantly exceeded by existing IMS primary and auxiliary stations today. Globally, the IMS seismic network provides complete coverage at magnitude 3.8, with about 80 percent of stations operational. For Europe, Asia, North Africa, and North America, the 90 percent probability is better: m_b = 3.4. As described in Appendices C and D, the detection capabilities shown for the Russian test site at Novaya Zemlya are even better than indicated in Figure 2-8, which shows only the result for primary IMS seismic stations, because it does not include the auxiliary IMS station in Spitsbergen.

The least sensitive seismic detection capabilities in Figure 2-8 are found in the southern hemisphere, particularly the southern oceans. Hydroacoustic capabilities (see corresponding section below) complement those of seismic for most of the southern oceans and lead to much better detection capabilities than do those of the IMS seismic stations alone. Hydroacoustic data are incorporated into approximately 20-30 percent of the IMS analyses of seismic events, where they can help improve location and screening (see section below on hydroacoustic monitoring).

For the purposes of detection, location, and especially event identification, the combination of seismic and infrasound techniques (see section below on infrasound) has also been expanding.

In Table 2-2, detection capabilities are converted into yields of nuclear explosions that would be detected by the IMS primary stations alone (see Box 2-1 above). All of North Korea, most of Russia, much of Saudi Arabia, and large areas of China consist of older rocks and are regions of efficient propagation of seismic waves. Hence the yields in column 3 are appropriate for them. Iran, much of Turkey, and other parts of the Middle East are regions of poorer propagation of seismic waves. Hence the yields in column 4 are appropriate for them. All of these capabilities are well below one kiloton. A new primary station started operation in Turkmenistan in late 2009. Its added capabilities are not considered in Table 2-2.

The capabilities shown in this table represent the minimum detectable seismic events likely to be included in IMS bulletins sent to national data centers. To conclusively confirm that a reportable event is the result of a nuclear explosion at such low yields would likely require additional evidence; for example, the collection of radioactive debris or possibly even an on-site inspection.

TABLE 2-2: Event Detection Capabilities Using IMS Primary Stations in 2007.

Probability of Detection Primary IMS Stations	**Magnitude (m_b)**	**Yield Hard Rock, Regions of Better Propagation**	**Yield Hard Rock, Regions of Poorer Propagation**
90 percent, entire world	3.8	0.22 kt	0.56 kt
90 percent, Asia, Europe, N. Africa	3.4	0.09 kt	0.22 kt

Note: The formulas used to calculate these figures are m_b = 4.45 + 1.0 log (yield Y in kt) for event yield (kilotons) in hard rock, regions of better propagation and m_b = 4.05 + 1.0 log (yield Y in kt) for event yield (kilotons) in hard rock, regions of poorer propagation.
SOURCE: Committee

Finding 2-5: One of the major advances in monitoring in the last 10 years is that most of the IMS seismic stations are operating now, and most of those have been certified for data quality (including calibration) and integrity (with respect to tampering and data authenticity). The threshold levels for IMS seismic detection are now well below 1 kt worldwide for fully coupled explosions. (See Chapters 2 and 4 for further discussion)

Other Seismic Monitoring

Seismic stations that are supplementary to those operated as part of NTM and CTBTO fall into four categories:

- Those that are part of the international Federation of Digital Seismographic Networks, which are open stations with data often available in near-real time to any interested user;
- National networks, from which data may be available upon request on an *ad hoc* basis;
- Stations operated by numerous smaller institutions or research groups (typically on a temporary basis) that in the past have acquired excellent data including signals from events of interest, and that allow tomographic methods to provide detailed models of 3-D Earth structure.
- In addition, Member States may establish stations as cooperating national facilities (CNFs), and use the data from those stations to supplement data from the IMS. These stations must be certified for operation and the data authenticated. The International Data Centre may use the data from these CNFs for the purposes of "consultation and clarification," as well as the consideration of on-site inspection requests.

These supplementary stations provide useful data; for instance, many non-IMS and non-NTM stations have been used to reveal new details and better locations of the 2006 and 2009 North Korean declared nuclear-explosion tests (e.g., Chun and Henderson, 2009; Kim et al., 2009; Ford et al., 2009; and Wen and Long, 2010). Some of the seismic stations used in these studies were available in near real-time.

Summary

Seismic technologies for nuclear explosion monitoring have improved significantly over the past decade. Much of the improvement is due to the use of regional-distance (< 1,600 km, or 1,000 mi) seismic recordings of broader bandwidth signals. Though the seismic technologies for monitoring nuclear-explosion tests are highly developed, they continue to evolve. In general, there is the potential to improve event detection, location, and identification substantially over the next years to decades.

- Continued development of high-frequency regional and local seismic methodologies will lower thresholds for the detection, location, identification and characterization of small events.
- Continued development of improved models of the Earth's crust and upper mantle to provide 3-D velocity and attenuation models will improve event location and identification accuracy.
- Continued development of seismic source models will allow prediction of potential explosion signals in untested emplacement geometries and geologies and would enhance monitoring capabilities.
- Continued development of numerical modeling capabilities tying together source and propagation models would enhance monitoring capabilities.
- U.S. capability to characterize and refine assessments of nuclear explosions would be enhanced by utilizing high-quality data from seismic stations that are becoming increasingly available in real or near-real time, especially those in and those adjacent to countries of concern to the United States.
- The use of better models to integrate seismic with other monitoring data have the potential to enhance monitoring.

Finding 2-6: Seismic technologies for nuclear monitoring have the potential to improve event detection, location, and identification substantially over the next years to decades.

Recommendation 2-4: The United States should renew and sustain investment in seismic R&D efforts to reap the rewards of new methodologies, source models, Earth models, and data streams to enhance underground nuclear explosion monitoring, regardless of the status of CTBT ratification.

Finding 2-7: Closer collaboration among the U.S. monitoring, NTM, national laboratory, and academic communities would help the United States keep up with new developments and technologies for seismic nuclear-explosion test monitoring.

Radionuclide Monitoring

Radionuclides are produced in nuclear explosions in the form of fission products of the nuclear explosive material in the device or by nuclear reactions with material in and surrounding the device, such as metal, dirt, or water (activation products). Radionuclides from a nuclear explosion are produced in high quantities relative to natural processes and can be detected when they are either released (or vented) into the atmosphere or deposited on the ground near the detonation point.

Radionuclides are detected as particulate matter or as noble gases, some of which, such as xenon and argon, are important indicators of a nuclear explosion. For atmospheric nuclear detonations, a large fraction of the radionuclides will be carried by wind and can be detected remotely.

Some radionuclides can reach the surface from underwater and underground detonations. In addition to radionuclides that enter the atmosphere or the surrounding medium immediately following detonation, certain radioactive gases from an underground nuclear explosion can be released slowly by seeping out through fractures that can occur over periods of weeks to months or more (Box 2-2).[15]

Radionuclide detection is an extremely sensitive technique. For example, the radioactive material liberated into the atmosphere by an atmospheric nuclear explosion would be detectable by samplers for more than a week, even if it were diluted by the entire earth's atmosphere. Conventional means, such as those used in the IMS, can

BOX 2-2 Radioactive Noble Gases

Radioactive noble gases can reach the surface and can be liberated into the atmosphere following a nuclear test, because these elements are nonreactive and therefore difficult to contain even when there is a concerted effort to do so. There are several radioactive isotopes of xenon noble gas (^{131m}Xe, ^{133}Xe, ^{133m}Xe, and ^{135}Xe) that are produced in high enough quantities from a nuclear explosion that they can be detected a few days to weeks after the explosion. In addition, ^{37}Ar is also produced in relatively large quantities via the $^{40}\text{Ca} + n \rightarrow {}^{37}\text{Ar} + \alpha$ reaction when neutrons from a nuclear explosion react with calcium in the dirt surrounding a surface or underground explosion. Only radioactive xenon is used by the IMS for remote detection, because of the higher amounts of these isotopes produced and the ease of the collection of xenon. For on-site inspections, both radioactive xenon and radioactive argon are targeted. Long-term seepage exceeding 300 days following an explosion is theoretically possible under some conditions via the detection of the 11.9-day half-life of ^{131m}Xe, the 5 day half-life of ^{133}Xe, and the 35-day half life of ^{37}Ar. The emission of noble gases from a cavity is more likely under scenarios in which cavity decoupling technology is used, because of the absence of shock heating that would take place in well coupled media, as discussed in Appendix E. This makes monitoring of radioactive noble gases an important part of the CTBT verification regime.

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[15] Seeping is caused by a process known as barometric pumping, which is the same mechanism that releases radon gas from the ground. See Appendix F for additional information on seeping and venting.

easily detect atmospheric detonations from nuclear explosions down to 0.001 kiloton.

Radionuclides are carried by weather systems and therefore over periods of a week or two tend to stay in plumes. Depending on the direction of the winds, these plumes could miss emplaced stations, such as those deployed by the IMS, but could be detected by mobile detection systems, such as those that are operated by some nations as part of their national technical means.

Nevertheless, it is very likely that in most places on Earth, radioactive particulate stations in the IMS will allow detection of atmospheric detonations below 1 ton of nuclear explosive yield. For other locations, detection may be accomplished through non-IMS technical means and detonations pinpointed through infrasonic or satellite technologies, as well as atmospheric transport backtracking.

Radionuclide detection functions synergistically with other detection methods, as indicated in Table 2-1. Radionuclides can be detected by sensors either in stationary or mobile platforms, and the samples can be either measured at the collection location or taken to a laboratory for processing and measurement. Because there are other processes that release fission and activation products into the atmosphere (i.e., nuclear fuel-cycle operations), radionuclide detection equipment commonly keys on specific signatures that are unique to nuclear explosions through the use of specific isotopes or ratios of activities of one isotope to another. The ratio of isotopes within a sample can also be used to determine the approximate detonation time of the explosion based on the rate of decay of the radionuclides in the sample.

Atmospheric transport modeling (ATM) is an important tool used to calculate the origin of detected radionuclides, as well as the probable future location of air masses. First, radionuclide concentrations that are collected at specific locations (or the lack of the presence of radionuclides), and the corresponding times are used to backtrack a plume to determine probable source locations consistent with the measurements. Second, ATM is used to predict the future location of a plume of radioactivity so that actions can be taken to collect airborne gases or particulates that may be present or, for example, to check the consistency between seismic and previously-emplaced radionuclide detection systems. ATM will in most cases be combined with other techniques such as seismic and infrasound technologies to accurately determine detonation locations. By combining these technologies, a more definitive determination regarding possible nuclear explosions can be made.

Changes Since the *2002 Report*

The most significant improvement in radionuclide detection since 2002 has been the development of radioactive xenon noble-gas detection. The concept of this type of monitoring as part of the IMS was considered new during the drafting of the Treaty, and therefore only 40 of the 80 Treaty-defined monitoring stations were specified as noble gas stations. The CTBTO decided in 1999 to conduct an International Noble Gas Experiment (INGE) to test aspects of the detection of radioactive isotopes of xenon (“radioxenon”) for the IMS.

The results of these experiments showed that sensitivities of the equipment generally exceeded all of the specifics laid out by the Provisional Technical Secretariat (PTS) for noble gas measurements (Auer et al., 2004). Shortly after the second phase of the INGE experiment began, commercial partners were identified, and now there are three commercial entities that have successfully produced radioactive xenon noble gas equipment that meet or exceed requirements for the IMS. Currently, 31 of the 40 noble gas systems planned are either installed or under contract.

One of the outcomes of the INGE experiment was that the radioxenon equipment that was proposed for use in the IMS was ready for certification and provided a useful tool for verification. At the start of the experiment, there was a single prototype technology available for radioactive xenon noble gas measurements, whereas today a working network of samplers collect and send data to the International Data Centre (IDC) in Vienna on a daily basis.

In addition to improvements in radioactive xenon noble gas monitoring, there have also been significant advances in particulate radionuclide detection, including more reliable mechanical cooling for high-resolution gamma ray spectrometers (Upp et al., 2005), better data analysis methods used by the International Data Centre to detect ever smaller quantities of radionuclides (Zähringer and Kirchner, 2008; Plenteda, 2002; Zähringer et al., 2009), and measurements of background levels of radioactivity at many locations around the world.

U.S. National Technical Means for Radionuclide Monitoring

Radionuclide Signal Detectability

The United States Air Force Technical Applications Center (AFTAC) operates WC-135 aircraft for detecting radioactive debris that could accompany nuclear explosions. AFTAC calculates the probable and accessible locations of the plume that could be released from either an underground, underwater, or atmospheric detonation and flies an aircraft to the location of the plume. The aircraft is equipped with external flow-through devices to collect particulates on filter paper and radioactive xenon gas in pressurized holding spheres. The radioactive xenon and the particulates collected on the filter paper are sent to a laboratory for analysis and evaluation for the fission products indicative of a nuclear-explosion test.

Radionuclide Event Location Accuracy

The detection of radionuclides is normally not the first sign of a possible nuclear explosion. Although seismic or other signals may be detected first, a capable radionuclide monitoring network may provide the key measurements that will confirm a potential event was nuclear. Meteorological conditions play a large role in identifying the possible source of a nuclear explosion. Once a potential event location has been identified using other technologies, ATM can be used to predict how an atmospheric plume will travel, providing opportunities to obtain samples for analysis. Using atmospheric transport calculations to backtrack from detections allows a rough determination of the location of emitted radionuclides, and much more accurate determinations of the specific location of a detonation can be made with other technologies (infrasound for atmospheric tests and seismic monitoring for underground tests). For the United States, if an airborne sampler can be flown close to the release point, more accurate estimates of event location are generally possible than would be the case using fixed distant samplers.

Radionuclide Event Classification

Fission and activation products can be produced by processes other than nuclear explosions. Atmospheric detonations will release millions of times more debris than any other process, with the exception of a serious nuclear reactor accident. In an accident scenario, however, it will be quite straightforward to discriminate the isotopes released from a reactor and those from a nuclear detonation based on the types and relative amounts of isotopes detected. The more challenging case involves discriminating underground tests that only release only a small amount compared to other man-made phenomena. Understanding the background of fission products that are in the atmosphere is key. A number of studies have been performed in the last 10 years to allow very good discrimination between nuclear explosion isotopes and those arising from other sources.

The types and relative amounts of isotopes that are emitted from a nuclear detonation are precisely calculable and well known for any type of fissionable material. These are the isotopes that are targeted for detection of nuclear detonations (see Box 2-2), and other sources that also produce fission isotopes are separated from these sources by comparing the detected isotope ratios with those expected from a nuclear detonation.

In the past decade, there have been significant improvements in the U.S. NTM for detection of radionuclides associated with nuclear-explosion testing. These include the development of new techniques to collect and measure radioactive xenon, substantial improvements in gamma ray spectrometry capabilities, new abilities to discriminate xenon backgrounds from man-made sources, nuclear detection algorithm development, improved ATM, and other technologies.

The NNSA Office of Nuclear Detonation Detection's Ground-Based Systems Nuclear Explosion Monitoring Research and Development (GNEMRD) program began in November 1993 in anticipation of the CTBT negotiations. The GNEMRD program has made significant advances toward technologies to both lower the background of radiation detection systems used for detection of airborne debris and develop more selective techniques to measure debris, while taking into account specific operational requirements. Specifically, since 2002 NNSA has developed:

- Automated, robust samplers and analysis algorithms for collection of both gases and particulates from nuclear explosions at levels much lower than the levels possible in 2002.
- Fundamental new ways to detect airborne debris, including data analysis algorithms and a deployable analysis system for measurements of short-lived xenon isotopes.
- Better understanding of global backgrounds of fission products that cause background in radionuclide detection systems.

Finding 2-8: AFTAC has demonstrated notable achievements over the past decade, including major enhancements in all aspects of radionuclide monitoring.

Recommendation 2-5: The United States should continue to actively support radionuclide collection, including R&D activities to better discriminate nuclear-test signature radionuclides from background, thus improving the ability to detect well-contained and lower-yield nuclear-explosion tests.

IMS Capabilities for Radionuclide Monitoring

Radionuclide data is handled completely separately from the waveform technologies (seismic, infrasound, and hydroacoustic). IMS station data are reviewed by radionuclide analysts and, depending upon the characteristics, are ranked from 1 to 5, with 5 being the most consistent with a possible nuclear source. ATM tools are then used to correlate multiple station detections together, tie them to a source region, and to any potentially associated waveform event. The CTBTO has developed software tools[16] that allow Member States to perform their own ATM using multiple meteorological models. Typically there are a few Level-5 detections each year arising from non-nuclear-explosion sources such as medical isotope reactors.

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[16] For example, the CTBTO has developed a software tool called "webGrape" that allows Member States to determine the probable location of emission of an air parcel, if radionuclides were detected at an IMS location.

Radionuclide results are reported in the Reviewed Radionuclide Event Bulletin (RREB), which is analogous to the REB for seismic monitoring.

Radionuclide Signal Detection

Based on the current coverage of the radionuclide detection stations listed in the Treaty, there is very little chance that an atmospheric detonation of even a modest size would go undetected by the IMS, largely due to the high sensitivity of radionuclide samplers in the network. Figure 2-9 illustrates a calculation[17] of the probability of detection of a 1-kiloton atmospheric nuclear detonation after 14 days by the IMS, based on a 79-station network and detection of a single species of isotope. The figure illustrates that the global coverage for atmospheric detonations is almost 100 percent, except for a few locations in the oceans near the equator where the probability is in the range of 30-90 percent. The coverage for xenon gas from underground detonations (Figure 2-10) is not as complete as for detection of particulates from an atmospheric detonation.

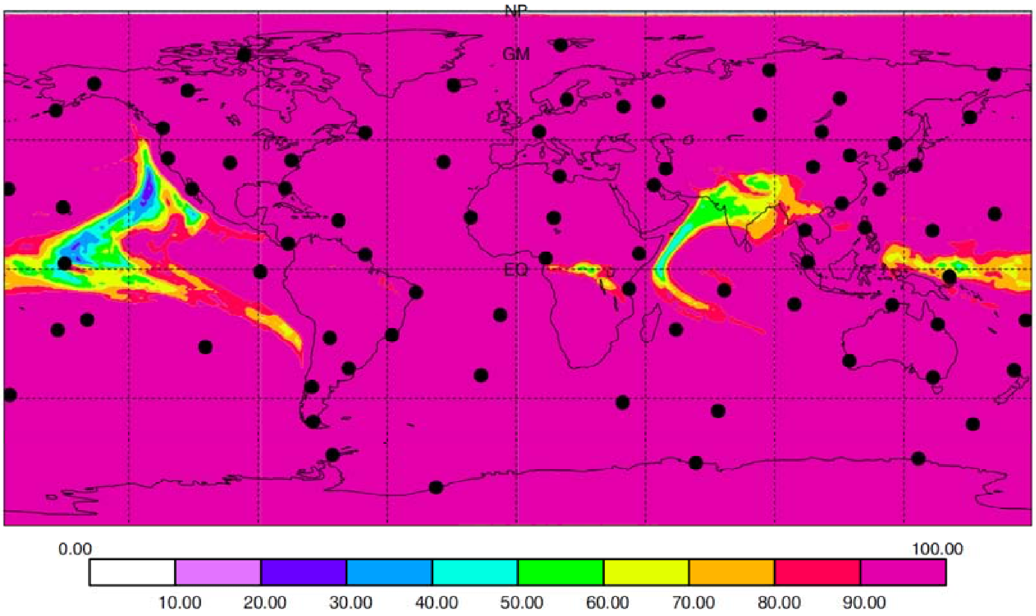

FIGURE 2-9: IMS coverage map for detection of radioactive particulates by one or more stations for atmospheric nuclear-explosion tests, showing the probability of detection (expressed in percent) of a 1-kiloton atmospheric nuclear detonation by the 79-station IMS particulate detection network (75 percent of stations certified as of February 2011) within 14 days. A global average detection probability for such an event is approximately 97 percent. The 80th particulate station, the location of which has not yet been decided, would presumably be located on the Indian subcontinent and would improve detection capabilities in that region overall. SOURCE: CTBTO

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[17] This calculation was performed by Andreas Becker from the CTBTO.

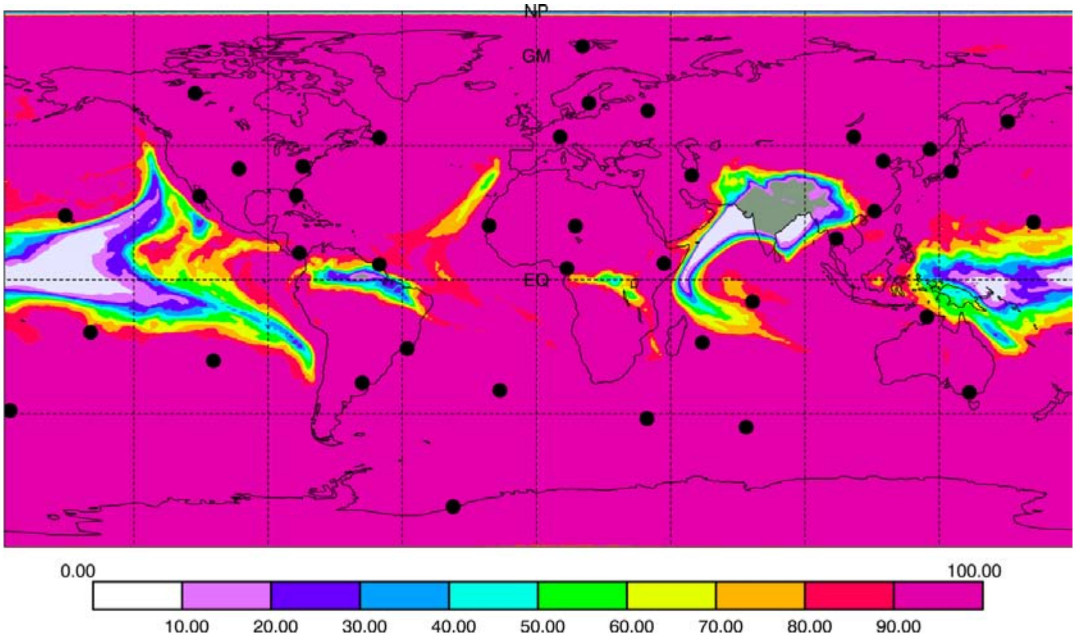

FIGURE 2-10: IMS coverage map for noble gas detection by one or more stations for underground nuclear-explosion tests, showing the probability of detection (expressed in percent) of a 1-kiloton underground nuclear detonation by the 39 station IMS noble gas detection network (65 percent of stations operational as of February 2011) within 14 days, assuming 10 percent of the radioactive xenon inventory is promptly vented from the detonation. A global average detection probability for such an event is approximately 88 percent. The 40th noble gas station, the location of which has not yet been decided, which would presumably be located on the Indian subcontinent, would improve detection probabilities in that region and overall. The Treaty allows for the entire 80-station network to eventually be populated with noble gas systems and under that scenario, a global detection probability for underground detonations would then reach near 97 percent. SOURCE: CTBTO

Radionuclide Event Location Accuracy and Classification

The same physical principles identified in the section on Radionuclide Event Location Accuracy above apply to the IMS as well.

Finding 2-9: In the past 10 years, the IMS radionuclide network has gone from being essentially non-existent to a nearly fully functional and robust network with new technology that has surpassed most expectations.

Finding 2-10: The IMS has made significant improvements in data processing.

Other Radionuclide Monitoring Capabilities

There are a number of national efforts in other countries to detect airborne radionuclides that would indicate a nuclear-explosion test, but these efforts are essentially NTM, and the number of open sources is relatively low. However, some national programs make atmospheric measurements of radionuclides for health and safety purposes—especially for remote monitoring for accidental releases from nuclear reactors—that could have some application to the detection of nuclear explosions, especially atmospheric testing. One such example is a network of radioactivity measurement systems throughout Germany, run by the Bundesamt für

Strahlenschutz (BfS), which makes continuous measurements of airborne fission products in Europe (Bieringer et al., 2009).

Finding 2-11: Ongoing measurement and understanding of global backgrounds of radionuclides relevant to nuclear-explosion monitoring are critical for improving radionuclide detection.

Recommendation 2-6: The United States should support research needed to understand the global background of radionuclides.

In addition, based on the discussion in Box 2-2 and Appendix F, we find the following:

Finding 2-12: In at least 50 percent of underground nuclear-explosion tests near 1 kt or larger, even those carried out by experienced testers, xenon noble gases may be detectable offsite above the detection limits of the IMS (0.1 to 0.2 mBq/m^3) from prompt venting of nuclear-explosion tests; also, long-term seepage of appreciable noble gases would be expected that could be detectable, both offsite and onsite.

Detection of such noble gases at fixed sampling sites would provide evidence that a test had taken place and, with the help of atmospheric models, could also suggest the source of the event. A CTBT cheater would have to take into account the significant probability that his test would be detected by this means.

Hydroacoustic Monitoring

Hydroacoustic monitoring for nuclear explosions in or near bodies of water has been utilized by the United States for many decades. Hydroacoustic signals can be generated by both in-water events and in-earth seismic events (e.g., earthquakes). An in-water source generates hydroacoustic waves (H-phase). A hydroacoustic wave can also convert to a seismic wave at a steep land–ocean boundary (called a T-phase), and similarly, a seismic wave can convert to a hydroacoustic signal.[18] In this sense, the hydroacoustic and seismic monitoring networks are complementary, and both play a role in monitoring the underground and underwater environment.

The CTBT specified a new hydroacoustic network as part of the IMS designed for monitoring Treaty compliance. The CTBTO IMS hydroacoustic network consists of six underwater stations and five seismic stations on islands.

Changes Since the 2002 Report

Fundamental improvements in the U.S. ability to monitor underwater nuclear-explosion testing have occurred since the *2002 Report* in two areas:

- The near completion of the IMS hydroacoustic network has improved global underwater monitoring capabilities. This network also enhances underground monitoring in and around the ocean basins.

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[18] In addition, we will refer to seismic waves that convert to acoustic waves just below the monitoring station as H-phases.

- Verification research and development has greatly improved the fusion of hydroacoustic data with seismic data, lowering detection thresholds in some regions by combining the two technologies.

Whereas the ability to model hydroacoustic signals continues to improve, the basic technology has not changed much since the *2002 Report,* where it is well described. Here, for completeness, we give a very brief review of hydroacoustic processing.

Hydroacoustic Signal Detectability

Hydroacoustic stations are designed to exploit efficient propagation in the sound fixing and ranging (SOFAR) channel in the deep ocean. For in-water events, when a hydroacoustic station has a clear SOFAR channel view to the source, the detection threshold is very low. If the SOFAR channel is blocked by land or does not exist due to low temperatures at high latitudes, detection capability is worse.[19] Figure 2-11 gives a map showing the CTBT IMS detection threshold for in-water explosions around the world using both seismic and hydroacoustic data. Thresholds in the open ocean are generally less than 1 metric ton TNT (and often less than 100 kg). Detection thresholds in coastal areas or inland bodies of water are generally around 10 tons, where the sensitivity in some cases is augmented by seismic networks.

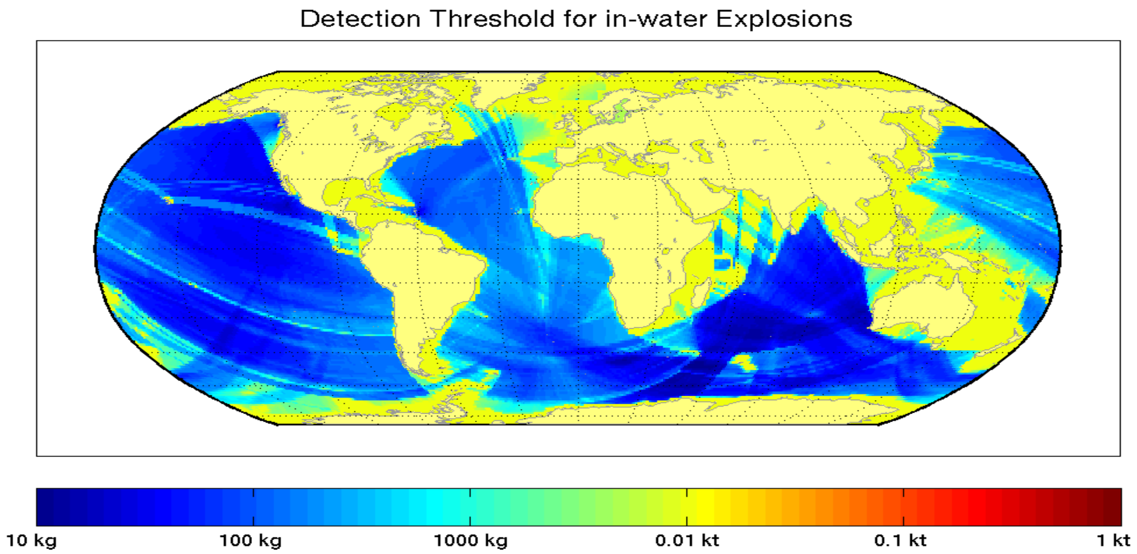

FIGURE 2-11: Map showing the IMS detection threshold in equivalent mass of TNT for in-water explosions detected on either the hydroacoustic or seismic IMS networks. Note that 1000 kg = 0.001 kt. Areas not covered by the hydroacoustic network—such as the Mediterranean Sea—are covered by the seismic network to a threshold of around 0.01 kt. SOURCE: CTBTO

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[19] Of direct relevance to hydroacoustic monitoring is the changing background noise field in the oceans. Deep-ocean ambient noise in the northeast Pacific has increased 10-12 dB in the band from 30-50 Hz in the last 40 years due to increased shipping traffic (McDonald et al., 2006). The Ocean Studies Board of the National Research Council convened in 2003 quotes 15 dB as the average increase in deep ocean noise since 1950 due to shipping (NRC, 2003). The bulk of noise radiated from modern cargo ships is also within the hydroacoustic monitoring band (Arveson, 2000). Observations of increased ice melt during the northern and southern summers, attributed to global climate change, could also result in increased seasonal ambient noise. Studies are underway to quantify this phenomenon, which could reduce detection capabilities.

Event Location Accuracy in Hydroacoustic Monitoring

In-water events can be located with relatively high accuracy using H-phases, depending on the number of stations and reflections used and proximity to the event, whereas in-earth event location using T-phases has fundamental and unpredictable accuracy limitations. Hydroacoustic location accuracy for in-water events is controlled by:

- *The network coverage*. For example, the IMS network coverage is sparse, with only 6 hydroacoustic and 5 T-phase island stations to monitor all of the earth's oceans. Coverage is best in the Indian Ocean.
- *Signal measurement error*. This is the error in measuring phase arrival time and back-azimuth bearing. Signal measurement error is much smaller for the H-phases than for the T-phases. For example, the IMS locates in-water events using as few as 2 H-phase stations, whereas T-phases are not used in location because of their large measurement error.
- *Model error*. This is the error in the seasonally dependent hydroacoustic propagation velocity model.

Location accuracy can be improved when reflected phase arrivals (e.g., from continents or island margins) are present and can be associated with known reflectors. However, hydroacoustic tracking of events on land or below the ocean floor yields degraded location accuracy.

Hydroacoustic Event Classification

There is no way using only hydroacoustic monitoring to distinguish between a large in-water chemical explosion and an in-water nuclear explosion. However, large in-water chemical explosions are extremely rare. For example, the IMS locates only a handful of purely hydroacoustic events each year. Any large in-water explosion event would merit careful and comprehensive analysis. In addition, in-water nuclear explosions would also release massive amounts of radionuclides into the marine environment and into the atmosphere, which might be detected using radionuclide detection technology.

To distinguish between an in-water explosion and some other kind of in-water or in-earth event, two methods are utilized by the International Data Centre for event screening: cepstral analysis (to indicate the presence of a bubble pulse) and the frequency content in the signal. Cepstral analysis measures the degree to which the signal has a repeating pattern. Such repeating patterns are characteristic of an in-water explosion, because the explosion gas bubble expands and contracts as it moves to the surface. It should be noted that shallow in-water explosions that vent to the atmosphere on detonation do not have a bubble pulse.

Most earthquakes that convert to a T-phase are depleted in high frequency energy, with little signal above 30 Hz. In contrast, in-water explosions show significant energy across the 1–100 Hz monitoring band. Consequently, events are classified based on their relative high-frequency energy content. This measure will effectively group in-water explosions in one population; however, that population will also include Antarctic ice events, submarine volcanic events, and some earthquakes that produce T-phases with significant energy across the monitoring band. Further screening based on location can identify ice and volcanic events.

U.S. NTM Hydroacoustic Monitoring

The U.S. maintains a hydroacoustic monitoring capability that meets the U.S. requirements for in-water event detection. U.S. monitoring is generally better than IMS hydroacoustic monitoring due to the great number of hydroacoustic sensors available to the U.S. NTM network.

IMS Hydroacoustic Monitoring

The CTBT IMS hydroacoustic network consists of an 11-station network consisting of 6 hydroacoustic (H-phase) stations and 5 T-phase stations (see Figure 2-12 below, where yellow marks hydroacoustic stations, red marks T-phase stations). The hydroacoustic stations were designed to exploit efficient propagation in the SOFAR channel in the deep southern oceans.

The IMS hydroacoustic monitoring network, with the exception of two stations, is operational and certified. One non-operational station is Crozet Island in the south Indian Ocean. The station is operated by France and has presented great difficulties over the years due to remoteness and the site environment. Options for the Crozet Island station are currently in active discussion at the IMS. The other non-operational station is Juan Fernandez Island, which was destroyed in March 2010 by the tsunami induced by the large Chile earthquake.

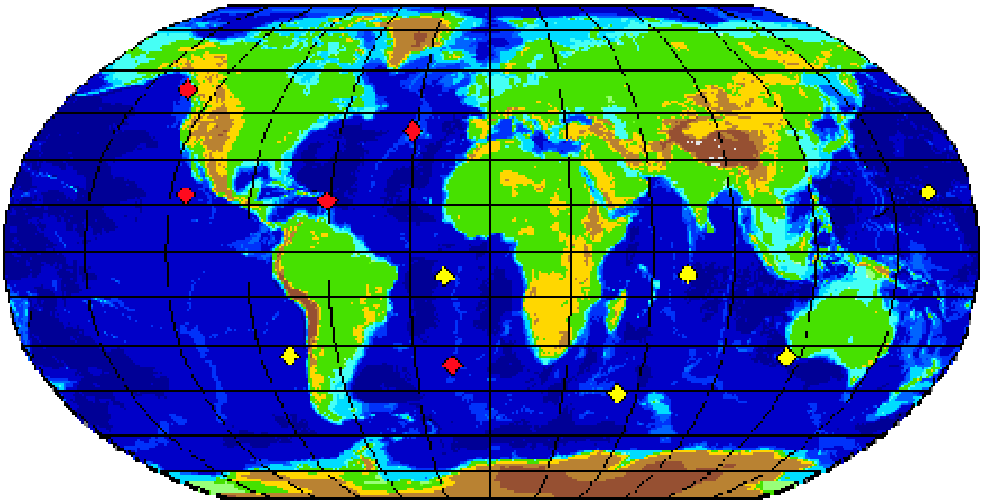


FIGURE 2-12: The IMS 11-station hydroacoustic network consists of 6 hydroacoustic stations underwater in the SOFAR channel (yellow symbols) and 5 T-phase seismic stations on land (red symbols). SOURCE: CTBTO

Finding 2-13: The IMS detection threshold for in-water explosions is 10 tons (0.01 kt) or below worldwide and below 1 ton (<0.001 kt) throughout the majority of the world's oceans.

Finding 2-14: As of 2010, two of the six hydroacoustic stations of the IMS were damaged and became non-operational after installation and certification; one will be restored.

Recommendation 2-7: The U.S. should assess the need for data from the damaged hydroacoustic stations and, if appropriate, work with the CTBTO to restore these stations to operational capability.

Hydroacoustic Research and Development Needs

Developments needed in hydroacoustic monitoring fall into two general areas: network assessment and event processing. Network assessment is the collection of prediction models backed with data that, where possible, allow prediction of network event detection, location, and identification capability. Network assessment software tools and databases need to be updated and further developed. Hydrodynamic source calculations need to be revisited and updated using a more realistic model for interface energy losses. Noise models for the hydroacoustic stations need to be developed based on the archived data to date.

Event processing encompasses the utilization of the network recordings to detect, locate, and identify explosive events. Recent research using back-azimuths and reflections could be exploited in routine hydroacoustic data processing to provide one-station or two-station event location and improve overall location and identification. Also, of high importance, is the further development of an explosion event database using past data where available and new events that may occur. Such a database will be important in developing effective identification techniques and testing IDC screening methods. Research is also needed to improve processing approaches that use hydroacoustic data in synergy with seismic data for event detection, location, and identification.

Infrasound Monitoring

Infrasound waves are sound waves with frequencies between 0.01 and 10 Hz, below the sensitivity range of the human ear. They are produced by explosions in the atmosphere and can be detected at great distances. They are also produced by ground motion from underground explosions and provide a complementary source of data to detect and discriminate underground nuclear-explosion tests. The IMS uses its infrasound stations to detect and locate atmospheric nuclear-explosion tests.

Changes Since the *2002 Report*

To establish an independent atmospheric detection/location capability for the parties to the CTBT, the IMS began in 2001 to establish an infrasound network consisting of 60 geographically distributed stations (see Figure 2-6). At the end of 2000, one infrasound station was transmitting data to the IDC. As of February 2011, 43 stations (72 percent of the planned infrasound network) have been certified and are contributing to the IDC. The first atmospheric non-nuclear event built only from infrasound arrivals was reported in 2003.

Traditionally, infrasonic detection and location methods have been borrowed from the seismological community and have not accounted for the complex effects of the atmosphere. In some instances, the IDC has had to shut down its automated infrasound system because it produced too many false alarms. Within the last few years, however, new methods for detection and location that are tailored for infrasound have been developed and show great potential for meeting the IDC operational needs (Arrowsmith et al., 2008; Modrak et al., 2010). In addition, high-resolution models of the state of the atmosphere in near real-time have been developed to realistically simulate the time/regional dependence of infrasound wave propagation in the context of local weather and wind patterns.

The resulting performance of the system with the present 42-station network allows explosions with a yield of 1 kt and greater to be detected across 80 percent of the Earth's surface. When the full proposed IMS network is operational, 1 kt explosions will be detectable across 90–95 percent of the Earth's surface. In some areas of the earth, much better detection levels will be possible. Recent studies (Le Pichon et al., 2008; 2009) have shown that where station coverage is favorable, as in the northern hemisphere, the infrasound network is capable of detecting and locating atmospheric explosions down to a level of tens of tons of TNT. The best performance is predicted around January and July when stratospheric winds are stable and strong. On the other hand, the best location of the event is in the spring and fall, when detection at a larger range of azimuths is more likely.

Finding 2-15: Infrasound detection is a valuable approach for monitoring atmospheric nuclear explosions.

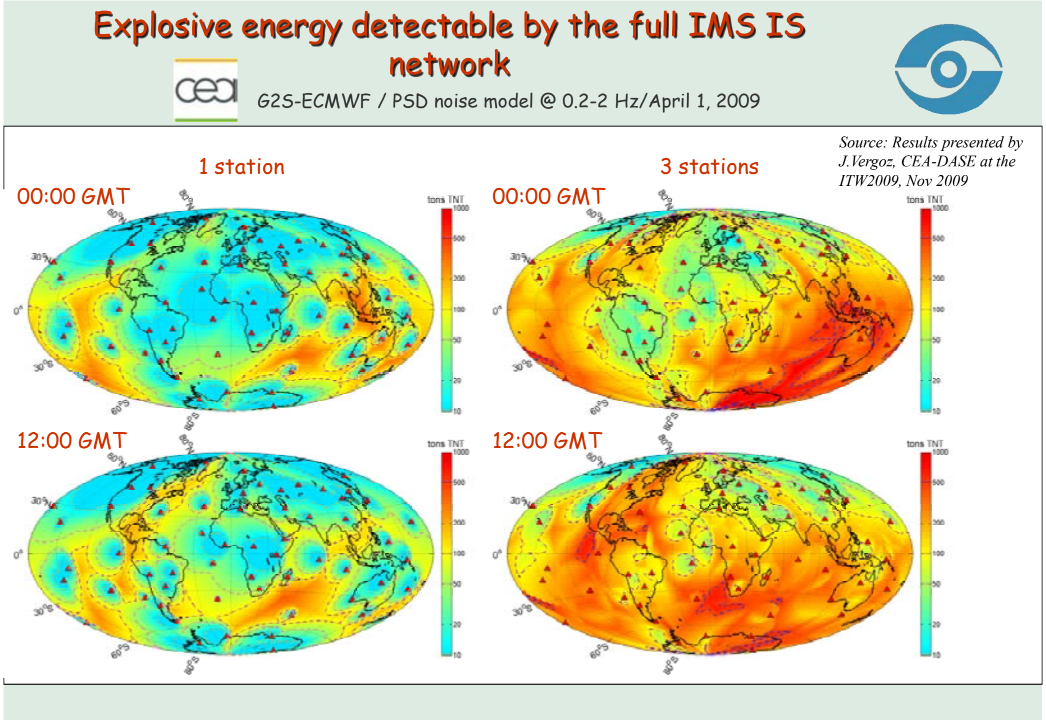
Although the IDC infrasound network is ostensibly for monitoring nuclear-explosion tests in the atmosphere, it has great potential to be used in parallel with seismic techniques to detect, locate, and identify underground or near-surface explosions.

Finding 2-16: Integration of infrasound with seismic data and analysis will provide better detection, location, and identification of explosions.

Infrasound Research and Development Needs

Infrasound detection research has generally received lower levels of funding due to the U.S. reliance on satellites and radionuclide-based techniques instead of infrasound for detecting atmospheric explosions. However, U.S. infrasound research has resulted in the discovery of the operational usefulness of seismo-acoustic measurements (the combination of local infrasound measurements with seismic signals for event discrimination). Due to high cost, the nuclear explosion monitoring community relies on other fields for R&D progress on meteorology, and field tests are limited to collecting measurements from tests conducted by others for different missions.

Significant improvements in capability are possible via validation of real-time atmospheric models and acoustic propagation algorithms. These models have been tested only on a limited number of ground-truth events. The fusion of acoustic propagation algorithms with detection and location methods will ultimately enhance capability. For instance, event discrimination is a new area of development within the infrasound community and requires much further research. Even so, the ability to produce coverage maps (see Figure 2-13) with confidence is a major development of the past decade.



Explosive energy detectable by the full IMS IS network

G2S-ECMWF / PSD noise model @ 0.2-2 Hz/April 1, 2009

Source: Results presented by J.Vergoz, CEA-DASE at the ITW2009, Nov 2009

FIGURE 2-13: The explosive energy detectable by the full IMS infrasound network. The scale, in tons of TNT, runs from 10 to 1,000. SOURCE: J. Vergoz, CEA-DASE, 2009

Satellite-Based Monitoring for NTM

Satellite-based nuclear explosion detonation detection adds an important capability of the USAEDS for detecting nuclear explosions in the atmosphere and serves as the USAEDS means for detecting nuclear explosions in space (see Figure 2-1). The objective of satellite-borne nuclear detonation detection instruments is to provide timely and accurate information that a nuclear explosion has occurred in the atmosphere or space environments, including its time and location of occurrence and an estimate of the yield. In the case of monitoring the CTBT, satellite nuclear detonation detection systems, if they continue to be deployed and maintained for this mission, will play an important role in conjunction with other elements of the USAEDS. Monitoring for nuclear explosions using satellites is not part of the CTBTO IMS system.

Satellite Detonation Detection Capability

The technical basis for detecting nuclear explosions in the atmosphere or in space derives from the U.S. atmospheric test experience, which has been studied extensively. Different phenomena are detectable at various altitudes depending on where the nuclear explosion takes place. Based on this knowledge and experience starting with the Vela satellites in the early 1960s, the United States has produced and maintained an impressive satellite nuclear detonation detection capability for continuous coverage of Earth and space. Modern coverage is provided by nuclear detonation detection payloads carried on multi-mission satellites (Global Positioning System [GPS] and, at geosynchronous altitudes, the Defense Support Program [DSP] satellites), which are procured and operated by the U.S. Air Force. The nuclear detonation detection sensor payloads are provided by DOE NNSA, whereas AFTAC receives the data and interprets it as part of the USAEDS.

Satellite Event Location and Classification

In the past 10 years, research sponsored by DOE/NNSA at the national labs has resulted in improved optical detection with better sensitivity and coverage, even in the presence of obscuration due to clouds, debris, etc. In addition, modern satellite electro-magnetic pulse (EMP) detectors are able to operate independently of the optical detectors and can now provide credible confirmation of an atmospheric nuclear explosion. The significance of this is improved timeliness and confidence in the detection and identification of atmospheric nuclear explosions. In the case of a high-altitude explosion occurring in the transition region, this information would also aid civil authorities in assessing the potential damage to ground-based infrastructure caused by EMP effects. Finally, advances over the past decade due to incorporating modern data processing and communications allow this vitally important information (i.e., the occurrence of a nuclear explosion) to be made available to the highest levels of U.S. authorities quickly and with very high confidence. For example, in the case of a nuclear explosion in space, the results of satellite detection of nuclear radiation would immediately be available to the military authorities in assessing the potential effects of an exoatmospheric nuclear explosion on vital U.S. space assets.

The Future of Satellite-Based Nuclear Detonation Detection Monitoring

Today there is uncertainty regarding the future of the U.S. satellite nuclear detonation detection capability. Modernization of the detector payloads for both upgraded GPS (GPS Block IIF and Block III) and the follow-on to the geosynchronous DSP satellites Space-Based Infrared System (SBIRS) has been accomplished. DOE/NNSA has continued to fund the national labs to develop the technically complex satellite detonation detection systems, including data processing and display systems. AFTAC continues to operate the satellite nuclear detonation detection portion of the USAEDS, including the anticipation of upgrades and improvements in the detection capabilities. The uncertainty in the future satellite nuclear detonation detection monitoring capability arises because the lead time for planning future Air Force satellite programs can be a decade or more and, once the planning and programming decisions are made, these satellite systems are very expensive to acquire and operate. Changes come slowly. It is not unusual for a transition to require a decade of time. Thus, during the planning stages, competition for scarce resources (e.g., size, weight, and power) on future satellites can be fierce. In this environment, all requirements receive intense scrutiny, including the nuclear detonation detection mission—in other words, whether the requirement for nuclear detection is still a sufficiently high priority relative to other military requirements to merit inclusion, or perhaps the nuclear detonation detection mission might be accommodated on other platforms, become important issues. Concerns with the latter option are that the alternatives potentially available are usually far in the future, are more costly, do not meet coverage requirements, or some combination of these. More detail on the potential loss of capability is given in Appendix G, which notes that satellite monitoring capability is needed for warfighting and space control missions, as well as for treaty monitoring.

Finding 2-17: Sustainment of the U.S. satellite monitoring capability to detect any nuclear explosion in the atmosphere or space, whatever its origin, will continue to be in the interest of the United States and its allies, regardless of whether the CTBT enters into force.

Recommendation 2-8: Enhanced satellite nuclear detonation detection systems should be deployed in upgrades to GPS (GPS Block IIF and Block III) and the follow-on to DSP, the Space-Based Infrared System (SBIRS). Provision for adequate ground-based data processing is also essential. Decisions regarding whether and at what level to maintain the satellite nuclear detonation detection capability should be made as part of high-level national security policy and acquisition assessments.

OPERATIONAL CAPABILITIES OF THE CTBTO

The committee was asked to assess what commitments are required to sustain an adequate international verification regime, including on-site inspection. The views below were developed following interactions with the staff of the Preparatory Commission of the CTBTO and a visit by a sub-group of the committee to the CTBTO in Vienna, Austria.

The budget available to the CTBTO is determined by the Member States to the Treaty. In principle, the States could agree to any level of budget needed to establish and operate the CTBTO monitoring network. The total annual operating budget for the CTBTO for 2009 was $100M, which funded all of the activities of the CTBTO such as installation and certification of the stations in the IMS, funding of the Global Communications Infrastructure (GCI), preparation activities for on-site inspections, post certification activities of the stations such as operations and maintenance of stations, reporting, analysis of data from the IMS, preparedness exercises, management of the organization, etc. (The U.S. contribution to the annual operating budget was $25M in 2009 and $30M in 2010.) In addition to the agreed budget allocated to the CTBTO, States also can make voluntary contributions to the budget as well as provide support to the verification regime, via contributions-in-kind. Although the States hosting primary and/or auxiliary stations may and typically do make voluntary contributions, including contributions-in-kind to defray these costs, the CTBTO must be in a position to cover the costs fully, if necessary, because there is no requirement for States that host monitoring stations to contribute. In addition, the CTBTO bears the cost of preparing and transmitting reports requested by the States and must train inspectors for on-site inspection.

In 2004–2005, the CTBTO performed a System-Wide Performance Test 1 (SPT1) to establish a performance baseline for the IDC and IMS. “Drawing upon SPT1, narrower focused exercises to test individual components of the system were conducted in 2007 and 2008. These exercises might lead to another system-wide performance test at a later time” (Dahlman et al., 2009; Zerbo, 2006).

The CTBTO has a competent and dedicated staff that is operating well. It has managed the significant increase in the number of certified IMS stations from three in October 2000 to 264 in February 2011, with an additional 17 stations installed and undergoing evaluation prior to certification.[20] These installed stations represent about 83 percent of the full network of 337 stations (321 plus 16 laboratories) and should approach 90 percent by the end of 2011. The CTBTO staff level, however, has changed very little historically, despite the very large increase in operating stations, data flow, and analysis. As a result, there are some signs of strain, primarily due to the long hours worked. To move to full-time operations after entry into force, the CTBTO will need a significant increase in staff.

In addition to collecting raw data, the CTBTO also generates a series of waveform-based (seismic, hydroacoustic, and infrasound) events lists (REB) and a series of radionuclide detections lists (RREB). The CTBTO also provides software, training to Member States and the potential for State-directed additional analysis, which could include additional non-Treaty station data.

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[20] See map at: *http://www.ctbto.org/map*.

To meet Treaty obligations at entry into force, all of these components will have to be fully operational. Sustaining the monitoring capabilities into the future will require further steps. For example, the CTBTO is subject to a number of political and funding restrictions outside its control. Examples of these include:

- a cap on the total number of employees (about 280), now limited by the provisional status of the organization;
- a slightly lower pay scale than their neighboring agency, the IAEA due to the CTBTO's provisional status;
- a number of limitations tied to the Treaty itself (e.g., confidentiality of data, auxiliary station data "by request" only, and the need to operate by consensus); and
- CTBTO employees' are currently being limited to a 7-year tenure. Exceptions are granted, but only for a few years. This is a potential problem for maintaining a core group of competent analysts, because it takes several years for analysts to become proficient.

Finding 2-18: Although the IMS is operating effectively, meeting the needs of CTBT entry into force will require more staff and easing of budgetary constraints.

Recommendation 2-9: The United States and others should ensure that priorities and funds are sufficient for IMS to meet ongoing needs, including after entry into force.

Table 2-3 summarizes the CTBTO's current provisional operations compared with what will be required when the Treaty enters into force. In many areas, the CTBTO already meets its Treaty requirements, but this is not true in all cases.

TABLE 2-3: Comparison of the CTBTO's Current Provisional Operations with Those That Will Be Required When the CTBT Enters into Force.

Function	Provisional Operation	Entry into Force
Hours of operation	People on duty only for business hours (Monday–Friday) as directed by Working Group B	Constant operation
Analyst training	Up to a year of training needed to reach high proficiency. The CTBTO conducts training classes in Vienna using the software to create a pool of potential analysts for future hires and to help staff Member States National Data Centers (NDCs).	
Reviewed Event Bulletins	~ 10 days	~ 48 hours*
Standard Event List (SEL)	Automated bulletins are generated in 1, 4, and 6 hours after an event	Level of automation and timelines currently meets EIF requirement
Screened Event Bulletin (SEB)	Lists events that have earthquake-like signals and that therefore should not be of concern as potential Treaty violations.	Screening algorithms may need updating as experience with the full IMS is gained.**

Radionuclide processing	80-station particulate network, 40-station noble-gas network	A plan for an 80-station noble-gas network will be considered.
Sensor Operation	24 hours a day	24 hours a day

Notes: * Automatic reviewed event bulletins (REBs) will be produced less than 48 hours from the end of the day on which the event occurred, 98 percent of the time. This will necessitate a significant increase in staff, particularly analysts.
** The majority of events not processed have m_b < 4.5. Because the 2006 and 2009 North Korean declared nuclear-explosion tests came close to being screened out by the M_s:m_b criteria, the Waveform Expert Group under Work Group B recommended modifying the rules, and the new M_s:M_b screening criteria were adopted in 2010.
SOURCE: Committee

IMS Construction and Operations

The CTBTO has done a good job of building and operating the IMS. The CTBTO appears to be on a solid path to have more than 90 percent of the network built, certified and close to meeting entry-into-force operational objectives by the end of 2010. Budgetary constraints have caused slower than optimal construction of the IMS, and fewer analysts are currently employed than are needed for 24-hour operation. The CTBTO has started to build maintenance and replacement costs into its budget estimates. The seismic and infrasound stations seem to have well-understood failure rates and sustainment budgets. The radionuclide stations have higher failure rates than desired and may need further failure analysis and hardware development both to meet entry-into-force operational objectives and reliable sustainment cost estimates.

Opportunities for Technical Improvements to CTBTO Capabilities

The CTBTO seismic monitoring system could be improved if auxiliary station data were available and incorporated into the automated system on a continuous basis. This would be straightforward to do technically, but because the Treaty states that auxiliary data is "upon request" and auxiliary stations are supported by the hosting state and not the CTBTO, making such a change is a political issue and does not seem to be under consideration at present.[21]

Finding 2-19: A technical exercise that tests the advantages of incorporating auxiliary seismic station data into the CTBTO's automated system would be useful to demonstrate the feasibility of this proposed improvement.

Finding 2-20: Location accuracy of events identified with waveform signals (seismic, hydroacoustic or infrasound) can be improved technically by better calibration to reduce the size of error ellipses and to improve detection and location accuracy. A technical review that evaluates calibration efforts, such as station tuning, phase labeling, and location accuracy, could identify ways to improve absolute location accuracy.

The CTBTO's International Scientific Studies Conference (ISS), which occurred in 2009, provided a way to bring CTBTO staff into contact with the broader community. These contacts

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[21] Note, however, that two points need to be appreciated:
(1) Lowering the magnitude level at which events are detected has the potential to increase the number of events that remain unidentified.
(2) If the auxiliary network is incorporated into a detection network, then the CTBTO could have a different type of obligation for maintenance of auxiliary stations.

should be encouraged and continued as a way to provide ideas, resources, and peer review needed to improve the CTBTO's performance. In addition, the CTBTO could make greater use of scientific community catalogs and bulletins (e.g., International Seismological Center [ISC], National Earthquake Information Center [NEIC], local bulletins) to evaluate its REB.

Finding 2-21: The CTBTO benefits from systematic, sustained interaction with the broader scientific communities involved in areas relevant to its mission.

On-Site Inspections

Article IV.D. of the CTBT provides that each State Party has the right to request an on-site inspection (OSI) for "the sole purpose . . . to clarify whether a nuclear weapon test explosion or any other nuclear explosion has been carried out in violation of Article I and, to the extent possible, to gather any facts which might assist in identifying any possible violator" (CTBT Art.IV.D.35). Inspection requests must be based on data collected by the IMS, National Technical Means, or both.[22] The OSI Request must be approved by the CTBTO Executive Council.

After entry into force, once an inspection request is submitted, which could occur after a lengthy political process, the location where an OSI may occur is determined from information from either the IMS or Member States NTM. The inspection area is limited by the Treaty to 1000 km^2 (390 mi^2), a location uncertainty that can usually be achieved with data from the IMS. Within the inspection area the Inspected State Party can declare restricted-access sites that can be no larger than 4 km^2 (1.6 mi^2) each. The Inspected State Party can declare up to a total of 50 km^2 (20 mi^2) of restricted-access sites. The restricted-access sites must be separated by a minimum of 20 m (66 ft). Unless stopped by the CTBTO Executive Council following the required 25-day report from the Inspection Team Leader, the OSI continues up to the allowed 60 days. A request for continuation to perform specified activities can extend the OSI for an additional 70 days. A request to conduct drilling to obtain radioactive samples can be submitted at any time during the OSI.

The conduct of an OSI consists of a continuing process to focus the search on the location of a possible nuclear-explosion test. For underground nuclear-explosion tests, the goal is to ultimately find the location of the explosion test and recover radiological evidence of a recent nuclear-explosion test by means of gas, liquid, or solid sampling. Technologies are used in three ways in this process: (1) to narrow the search area to one or more subareas, (2) to identify specific sites within these subareas for application of very localized OSI measures such as the detection of relevant radionuclides emitted by the detonation, and (3) to find direct evidence of the nuclear character of the suspect event.

The Treaty's OSI provisions provide for the use of a broad range of technologies, including visual inspection from the ground and during overflight, seismic aftershock monitoring, radionuclide measurements, multispectral imaging, environmental sampling and analysis, geophysical technologies, and drilling. Within the list of inspection technologies, drilling requires a special request to the CTBTO Executive Council, a majority of which must approve the request.

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[22] Based on experience with other treaties, some doubt it will prove possible to garner the necessary 30 votes to authorize an inspection from the 51-member Executive Council. The *2002 Report* discussed this point and concluded that on-site inspection "constitutes a deterrent to treaty violation whether or not an inspection actually takes place, and it provides a mechanism for the innocent to clear the record" (pp. 55-56). The committee agrees with this conclusion; therefore this section is limited to assessing what could be gained from an OSI if it were to occur.

When the ratification of the CTBT was considered by the U.S. Senate in 1999, there was limited experience with how the OSI process would work. Since then, the CTBTO mounted a significant Integrated Field Exercise in 2008 (IFE08), during which a mock inspection took place at the former Soviet nuclear-explosion test site at Semipalatinsk, Kazakhstan. Planning and performance of the exercise did not mimic the timeline of a real inspection, but the CTBTO was able to work through the challenges of fielding large amounts of technical equipment; negotiating access by the mock inspection team with the mock inspected State; dealing with Treaty constraints; and identifying a number of logistical, scientific, and technical areas that need further development, such as communications, deep penetration geophysics, noble gas sampling and analysis, multi-spectral imaging, and active seismic surveys (CTBTO, 2008).

The Effectiveness of an OSI

Several factors can influence the effectiveness of an OSI: the size and placement of the supposed nuclear-explosion test; constraints such as Treaty-allowed managed access areas; the expertise of inspectors; time since the detonation; evasive actions that are taken before, during or after the presumed nuclear-explosion test, such as containment or shrouding of equipment; and the precision and accuracy of location by monitoring.

Given the difficulty and uncertainty associated with the containment of nuclear explosions, a nuclear-explosion test of sufficient size to be detectable is likely to result in radionuclide evidence (depending on the time since detonation) that could be detected during an OSI, and in fact radionuclide evidence detected remotely in one or more IMS stations may be one of the factors on which an OSI request is made. The extent of radionuclide evidence will depend on whether the explosion is successfully contained, and it may be necessary to obtain a fairly accurate event location (within a few km for the case of gas migration and within ~100 m for the case of drilling) in order to find such evidence. In addition to radionuclide evidence, other evidence associated with nuclear-explosion testing, such as detection of a borehole casing or other nuclear-explosion test artifacts, evidence of containment measures, disturbed ground, and/or location of the explosion cavity or rubble zone, may be considered sufficient.

Some of the radionuclides associated with a nuclear-explosion test are long-lived radioactive noble gases, which are known to seep slowly from a nuclear explosion site (Carrigan et al., 1996), and can be present at the surface at detectable levels for hundreds of days following a nuclear-explosion test, even at yields of 1 kiloton and less. As Figure 2-14 shows, detections under an OSI are probable with noble gases alone if conducted within 150 days of the event, and longer if detection thresholds are improved.

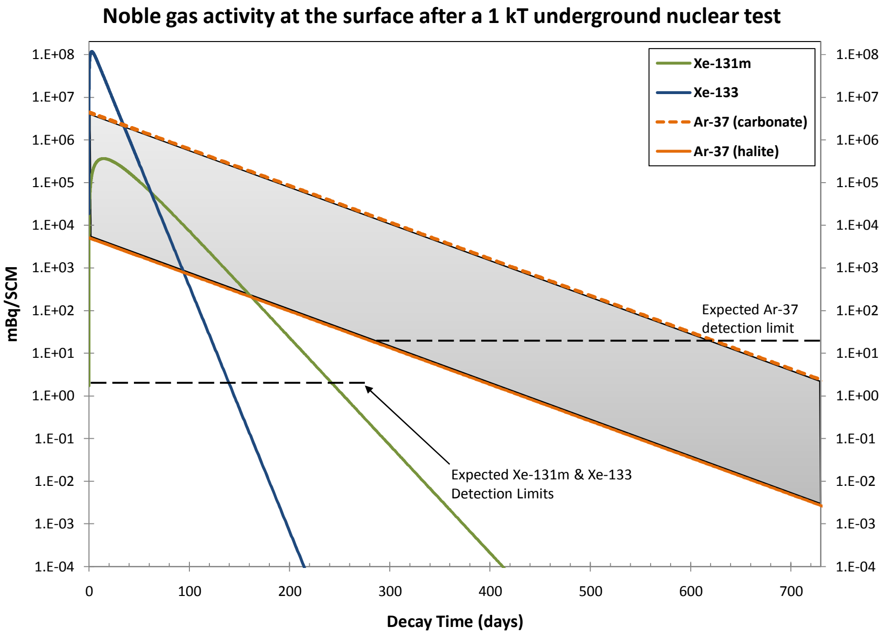

FIGURE 2-14: Plot of the approximate surface concentrations of the noble gases expected after a 1-kt nuclear detonation. The horizontal lines represent the detection limits that are expected from instrumentation that will be used during an OSI. The plot shows two curves for xenon (Xe-131m and Xe-133) and a range of values (shaded in grey) for argon (Ar-37). The latter corresponds to the concentration of Ar-37 that would be expected, over the range of values of calcium content that could be encountered during an OSI. SCM: Standard cubic meter of air. SOURCE: Adapted from Carrigan et al., 1996

In the case where an Inspected State Party (ISP) has violated the CTBT and attempts to thwart an OSI through the use of restricted-access areas allowed in the Treaty, it could actually make the job of the inspectors easier because the restricted-access areas may provide a map of the most interesting locations to perform environmental sampling. Even with restricted-access areas, inspectors could still operate equipment as close as 1,000 m to ground zero. This distance is expected to be close enough for both gaseous noble gas radionuclide measurements and geophysical techniques to be effective, as well as for slant drilling to reach the cavity.

Although it is somewhat scenario dependent, it is likely that in the 0.1 to 1 kiloton range of yields, there will be significant aftershocks; possible surface disturbances, such as visible and detectable cratering and fracture zones; human-made artifacts; and/or radionuclides at the surface that have vented from the nuclear explosion. Also, the Treaty allows the use of magnetic, electrical, and gravimetric techniques to assist in the detection of borehole casings and other underground structures and artifacts that will aid in pinpointing the location of a supposed nuclear-explosion test.

Unless other factors not guaranteed were used or detected, such as human intelligence or other evidence associated with nuclear-explosion testing as discussed on the previous page, it is likely that the effectiveness of an OSI to detect a test much below about 0.1 kilotons of yield would be low.

The requirements on evidence needed for the Executive Council to call an OSI may be so high that an OSI is never called. Moreover, if an OSI is called, some believe that treaty provisions for managing access to the site could limit the effectiveness of an OSI. However, our assessment is that if the United States had enough evidence to call for an OSI, it would likely have enough information from NTM and other sources to determine whether a nuclear explosion had taken place.

Finding 2-22: A CTBTO on-site inspection (OSI) would have a high likelihood of detecting evidence of a nuclear explosion with yield greater than about 0.1 kilotons, provided that the event could be located with sufficient precision in advance and that the OSI was conducted without hindrance.

Transparency/Confidence Building Measures

Any monitoring system intended to support verification of Treaty compliance—whether the CTBT's IMS, National Technical Means or other systems—has to be considered potentially imperfect. The system will have sensitivity, as well as resolution in space and time, below which events are unreliably detected; or parts of the system may occasionally break down. Such eventualities call for additional mechanisms, including confidence-building measures, to enhance Treaty verification.

There are many opportunities for confidence-building measures to support CTBT monitoring. For example, China, Russia, the U.S., France and the UK all claim to sustain nuclear arsenals through stockpile stewardship programs involving no nuclear explosions, and there are many aspects of these programs that can be discussed openly and in a manner enhancing mutual confidence.

Several areas that could be considered are:

1. *Plutonium Science*: There is an ongoing series of conferences at which researchers from the United States, the United Kingdom, France, Russia and (most recently) China discuss the basic science of plutonium. Though sensitive topics are avoided, the exchange of information is useful for these nations' technical communities. In addition to the scientific information that is communicated, simply evaluating the level of expertise available in each country provides significant insight about competencies and capabilities.
2. *Subcritical Tests*: Advanced nuclear-weapons states conduct subcritical tests, often at past nuclear-explosion test sites; these are by definition compliant with the CTBT and are below the sensitivity of any remote-monitoring system. How does the testing nation assure sub-criticality, however? What procedures are in place, and what is the combination of computational simulation and experimental measurement used to document subcriticality? Although details are likely to be too sensitive to be discussed, many aspects of the procedures used can be shared among individual nations. As demonstrated during the U.S.-Soviet Joint Verification Experiments of the late 1980s, one could even allow close-in monitoring of one nation's subcritical tests by another nation, with appropriate protection of classified information.

Other opportunities involve collaboration in closely related scientific disciplines, such as inertial confinement fusion (ICF) for producing energy or the study of warm dense matter (WDM) at conditions existing deep inside planets. These involve major experimental facilities that can be made available to users worldwide, with appropriate controls, including non-nuclear as well as nuclear-weapons states.

In addition to such activities in basic research, cooperative efforts in monitoring can significantly enhance confidence by engaging scientists and engineers from all nations around the world. This is already well documented in seismology, a field largely devoted to mitigating the hazards of earthquakes, as well as documenting the structure and dynamics of our planet. Similarly, atmospheric monitoring—and global environmental monitoring more generally—could be greatly enhanced through cooperative measurement and modeling efforts if, for instance, it is applied to data sharing on issues related to radiological incidents and emergency response, and documenting spatial-temporal patterns in abundances of carbon dioxide, other greenhouse gases, dust, or industrial pollutants.

Confidence-building measures are best established on a bilateral (or, possibly, limited-multilateral) basis in order to ensure protection of sensitive information. For example, certain technical details that can be shared between advanced nuclear-weapons States should not be revealed more widely, for fear of proliferating weapons-relevant knowledge. Also, there are many examples of information considered classified by one nation but not by another, thereby limiting the extent of cooperation. This means that confidence building should be pursued distinct from and in parallel with the CTBT, thereby complementing the monitoring and other capabilities associated with the Treaty regime. The cooperative measurement of radionuclides in the atmosphere is an example of an area that could lead to confidence-building and data exchange in the future.

Finding 2-23: There are many opportunities for confidence-building measures to support nuclear explosion monitoring, particularly through engaging scientists and engineers in cooperative efforts.

Recommendation 2-10: The United States should pursue bilateral (and, to the extent justified and politically feasible, limited multilateral) programs of scientific cooperation for purposes of confidence building in support of monitoring nuclear explosions. These programs should be periodically reviewed for effectiveness and for appropriate controls on information.

Test Site Transparency

Because of the detection limits at extremely low yields and the lack of a clear definition of "nuclear test explosion," transparency measures at known test sites could become an important adjunct to the Treaty and merit special consideration.

One of the actions that a country, and especially a nuclear weapon state, can take to show that it is acting in good faith in complying with the CTBT is to grant access to its nuclear-explosion test site, including allowing some types of non-sensitive measurements to take place at the test site. Allowing continuous measurements at a test site would also decrease the detection threshold significantly for that location.

The U.S. Department of Energy/National Nuclear Security Administration (DOE/NNSA) recently conducted a series of experiments to test technologies that could be used under a test site transparency regime. Technologies evaluated included geophysical, ground-based visual, remote monitoring, overflight, and radiological technologies. In addition, a technical evaluation matrix was introduced to demonstrate how a set of criteria could be used to prioritize possible monitoring technologies. Those criteria included relevance, intrusiveness, detection sensitivity, measure confidence, equipment factors, personnel factors, and composite (an overall assessment).

The subcritical experiment carried out at the test site contained on the order of a few kilograms of explosive, and this amount was easily detected by seismometers approximately a kilometer away from ground zero. In addition, radioactivity sensors were placed near the detonation point to verify that no radioactivity was emitted, such as xenon noble gases. These measurements showed that it is possible to conduct a series of null-measurements at a nuclear-explosion test site and give some level of confidence that the activities were not consistent with a nuclear-explosion test. NNSA concluded that, among other technologies, passive seismic, acoustic, radioactive xenon noble gases, and video would be effective for test site transparency applications.

The technologies demonstrated during this experiment could have applications to a long-term monitoring strategy at a test site, which might be an option for policy makers to have confidence that activities below the detection limits of the IMS or NTM are consistent with the CTBT.

Although in principle it would be desirable to improve test site transparency with all States possessing nuclear weapons, the United States should give priority to Russia and China. They are the States whose weapons programs are of the greatest strategic concern. They are also the States most capable of benefiting from very-low-yield testing (yields up to about 1 ton, fully coupled; see Chapter 4). Transparency measures with nuclear-capable States outside the NPT would be more difficult to agree on politically and less important strategically.

Finding 2-24: Test-site transparency agreements can provide a mechanism for mitigating concerns about very-low-yield testing (yields up to about 1 ton).

MONITORING AND THE NORTH KOREA NUCLEAR-EXPLOSION TESTS

The two announced Democratic People's Republic of Korea (DPRK) nuclear-explosion tests of 2006 and 2009 provided practical opportunities to exercise the monitoring capabilities of the technologies discussed in this chapter. The results are discussed in Box 2-3.

BOX 2-3 The 2006 and 2009 DPRK Nuclear-explosion Tests

DPRK Status: The DPRK has not signed the CTBT; it withdrew from the NPT in 2003. In 2005, it declared that it possessed nuclear weapons.

2006 Test: On October 9, 2006, the DPRK declared that it had conducted a nuclear-explosion test.

- *Seismic signals:* registered magnitude 4.1 as reported by the CTBTO IDC Reviewed Event Bulletin (REB) (22 stations reported—14 primary; 8 auxiliary).
- *Radionuclides:* Xe-133 was detected approximately 14 days following the detonation by the IMS station in Yellowknife, Canada; Xe-133 and Xe-133m were detected by Swedish researchers working in South Korea.
- *Infrasound:* none reported.
- *U.S. Assessment:* On October 16, 2006 the U.S. Director of National Intelligence (DNI) released a statement: "Analysis of air samples collected on October 11, 2006, detected radioactive debris which confirms that North Korea conducted an underground nuclear explosion in the vicinity of P'unggye on October 9, 2006. The explosion yield was less than a kiloton" (DNI news release, 2006).

2009 Test: On May 25, 2009, North Korea declared it had conducted a second nuclear-explosion test.

- *Seismic signals:* Registered a magnitude 4.5 as reported by the CTBTO IDC REB (61 stations reported—31 primary; 30 auxiliary)
- *Radionuclides:* none reported.
- *Infrasound:* Very small signal detected (e.g., Che et al., 2009).
- *U.S. Assessment:* On June 15th, the U.S. DNI released a statement that "North Korea probably conducted an underground nuclear-explosion test… (t)he explosion yield was approximately a few kilotons" (DNI news release, 2009).

Background: The DPRK has relatively few natural earthquakes per year compared to other countries in the region (e.g., China, Japan and South Korea). Natural earthquakes in the DPRK above magnitude 4 occur only once every few years, so the seismic signal stood out as unusual even before the DPRK government made its announcements. There are several IMS primary and auxiliary seismic stations within 1,200 km (750 mi) of the DPRK. Within the same distance there are additional non-IMS seismic stations that produce publicly available data and that were used by seismic researchers to analyze the tests in the days immediately afterward. In addition, China, Japan and South Korea each maintain dense networks of seismic stations to monitor earthquake hazards in the region. Although the data from these stations are not all publicly available, researchers in these countries have used them in analysis of the DPRK tests (e.g., Hong et al., 2008). In the region, earthquakes are routinely reported at levels of magnitude 3 and below; mine blasts and industrial chemical explosions are usually less than magnitude 3.5.

Observations:

- The seismic signals from the two events clearly indicate that they were explosions and not earthquakes. The 2006 nuclear explosion was an excellent real world test of empirical seismic methods for a sub-kiloton explosion in a new region and the discrimination methods worked very well.
- A question surrounding the two DPRK tests is why radionuclides were reported following the 2006 test but not following the 2009 test. Many, if not most, tests in the range of 1 kt have resulted in the release of detectable levels of radioactive noble gases. Containment of radionuclides following a test is complex, but it is thought that containment may be harder for a smaller test than for a larger one because it may be more straightforward to establish a "stress containment cage" for larger tests (see Appendix D). No system is perfect and the failure to detect in one case does not invalidate the utility of such a detection network.

The two DPRK tests made it clear that if multiple nuclear-explosion tests occur in the same region, then relative ("differential") methods of detection, location, discrimination and yield estimation can be brought to bear on the verification problem.

3

SUSTAINING U.S. TECHNICAL CAPABILITIES UNDER THE CTBT

Two technical programs that are essential to maintaining U.S. technical capabilities under the CTBT are the nuclear weapons program, including both DOE/NNSA and DOD components, and the treaty monitoring and verification program. Both are coupled to an important U.S. competency to understand and assess foreign nuclear weapons programs and technical changes. The sustainability of these essential U.S. and international competencies hinges on the definition of clear expectations and the provision of sufficient resources to allow those expectations to be met. These competencies are needed whether or not the U.S. ratifies the CTBT. In this chapter the committee reviews workforce, budgetary and management issues that were identified in sustaining these programs and suggests a modified set of U.S. safeguards that should be adopted to assure their sustainability.

OVERVIEW AND *2002 REPORT* FINDINGS

The *2002 Report* authors were not tasked to review sustainability issues, as is the case with this report. Nonetheless, the *2002 Report* did make some observations on the issue, especially regarding the workforce. The report stated that:

> "It is self-evident that a highly motivated, competent workforce throughout the complex, supported by a modern infrastructure and adequate budgets, is of overarching importance." (p. 27)

> The *2002 Report* also noted that:

> "Attracting and retaining a high-quality workforce in the nuclear-weapons complex will require adequate budgets, other clear signals about the future program direction and scope, long-term program commitments to technically challenging assignments, and greater attention to quality-of-work-life issues…" (p. 1-2)

It further said that the three nuclear weapons laboratories and the production complex were finding it difficult to retain their top technical talent and to recruit replacements due to attractive career opportunities in the private sector, uncertainties in the future of the nuclear weapons program, and other factors. These comments reflected the findings of the Congressionally mandated report from the Commission on Maintaining United States Nuclear Weapon Expertise, which recommended actions essential to recruiting and retaining the talented workforce needed for national security (Barker et al., 1999).

CHANGES SINCE THE *2002 REPORT*

The need to recruit and retain a talented and highly motivated workforce throughout the nuclear weapons complex has been recognized in many studies, both before the *2002 Report* and after. Some of the key findings and recommendations of more recent studies are:[1]

- A new vision is required regarding the U.S. strategy for nuclear deterrence and the competencies that are required to sustain it (DSB, 2008);
- Managers should identify the skills base essential to sustain current systems and to design, develop, and operate replacement systems (DSB, 2008; Congressional Commission, 2009; Task Force, 2009);
- Gaps in the skill base for assessing foreign nuclear programs should be filled (DSB, 2008), and labs should be able to work directly with the intelligence community in assessing such programs (Congressional Commission, 2009);
- Follow-on nuclear weapons designs should be explored (DSB, 2008);
- Organizations within the complex should maintain selected nuclear skills by managing their application in related non-nuclear applications (DSB, 2008; Congressional Commission, 2009; Task Force, 2009);
- Excessive bureaucratic regulation and micromanagement of the workforce by DOE and NNSA should be eliminated (Congressional Commission, 2009; Task Force, 2009).
- The decline in DOD management attention to nuclear matters is evidenced by a dramatically reduced workforce…. The remaining workforce lacks both depth and breadth of nuclear expertise (U.S. Secretary of Defense Task Force, 2008).

The many studies that have commented on nuclear complex workforce issues over the past 10 years have also noted some bright spots associated with key scientific programs and facilities, such as the Advanced Simulation and Computing (ASC) program; the National Ignition Facility (NIF) at LLNL; the Dual-Axis Radiographic Hydrodynamic Test Facility (DARHT) at LANL; and Microsystems and Engineering Sciences Application Facility (MESA) at Sandia. These programs have provided state-of-the-art computing and experimental facilities required for scientists to advance the stewardship mission in the absence of nuclear-explosion testing. Although most recent reports judge the current workforce to be of high quality, the prevailing tone is one of concern for the future. They note that older facilities within the complex (both laboratory and production) are showing signs of neglect (Congressional Commission, 2009). In addition, morale among the laboratories' scientists and engineers has suffered due to declines in funding and the lack of a clear, high-level U.S. government affirmation of the importance of their mission (Defense Science Board, 2008). This was also reflected in the committee's discussions with the nuclear weapons laboratory directors.

SUSTAINING U.S. NUCLEAR WEAPON PROGRAMS

Workforce and Budgetary Issues

Both annual funding and the number of full-time employees for NNSA's laboratory-based programs are near their 1998 levels, after going through a buildup and decline. It is difficult to draw firm conclusions about the health of the U.S. nuclear security programs from such gross

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[1] Many of these reports contain material that goes beyond the scope of this committee's responsibilities. We include reference to their conclusions to help provide context for our discussions.

data alone. For example, the quality of employees and the kinds of expertise they possess are more important than their absolute numbers, but data at this level of detail are hard to come by. Nevertheless, the committee notes that several developments since 1998 indicate cause for concern:

- *The workforce is aging.* The Henry L. Stimson Center report found that the fraction of the DOE laboratories' "essential workers" who are over 50 years old had grown to 40 percent, up from 34 percent just ten years earlier (Task Force, 2009). This raises concerns that the laboratories are not attracting and retaining the young scientists and engineers that will be necessary to sustain the complex far into the future. Bringing new talent into the laboratories may be critical in the near term if there is to be any meaningful overlap between new scientists and their predecessors who have first-hand nuclear weapons design and testing experience.
- *Gaps are developing in critical skills areas.* Recruiting and retention of adequate numbers of trained people in critical skills areas has been a particular challenge. Significant gaps in critical skills exist due to a combination of workforce demographics and/or reduced level of stockpile work. The Defense Science Board (DSB) Report on High Performance Computing reached similar conclusions; for example, DSB found that between FY 2002 and FY 2010, the number of employees involved in integrated computing at LLNL declined by one-half and at LANL by two-thirds; the conclusion reached was that the ability to maintain independent code assessments is threatened (DSB, 2009). The recent DOE-wide, two-year salary freeze exacerbates the workforce issues in the computer skills area because of the intense commercial marketplace for individuals with those competencies.
- *The stockpile is aging.* The United States is entering a decade in which substantial effort must be expended in life-extension programs (LEPs—see discussion in Chapter 1). Under fixed or declining funding, the design and production support required for the LEPs directly competes with support needed for other activities (e.g., surveillance, exercising workforce skills, assessing foreign programs, etc.).
- *The infrastructure is aging.* The aging physical infrastructure of the nuclear weapons complex is a bottleneck limiting both progress towards sustainability and the requirement of exercising the workforce in state-of-the art competencies (also discussed in Chapter 1).
- *Non-technical areas absorb an increasing fraction of the budget.* There has been a substantial resource shift from technical programs to security, safety and environmental programs in the past decade. As one example, the emphasis on environmental, health, safety, and security aspects of nuclear weapons development has increased,[2] with NNSA's Defense Programs safeguards and security funding growing from about $400 million in FY 2001 to over $850 million in FY 2009 (NNSA, 2009). New management contracts at LANL and LLNL have also diverted funds from

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[2] A recent National Research Council study on nuclear forensics stated the problem more starkly: "Pressure for increasingly stringent interpretation of environmental, safety, and health (ES&H) goals has made it increasingly challenging to work with materials and equipment that emit radiation or are otherwise hazardous. This problem is particularly acute at DOE and NNSA facilities where concerns about health and safety can, in some cases, add a substantial time and cost burden to, or even preclude, the performance of tasks that are essential to national security" (NRC, 2010). In July 2010, the NNSA Administrator issued NNSA Policy Letters (NAP) 70.2 (Physical Protection) and 70.4 (Information Security). These documents are intended to simplify requirements. The committee applauds the intent of the action but has not reviewed the documents in detail.

> technical work due to increased fees and loss of tax-exempt status.[3] A major effect of those new contracts was to increase indirect costs substantially, which at LLNL resulted in substantial layoffs, including senior scientists. The layoffs resulted in a decline in morale among the retained employees and inevitably make future recruiting and retention more difficult.

Finding 3-1: A decreasing fraction of the budget for the nuclear weapons program is available for the actual technical work that must be accomplished to sustain the U.S. deterrent.

The committee is encouraged that the recent FY 2011 budget request for NNSA's weapons activities is $7.0 billion (an increase of 9.8 percent over the FY 2010 appropriated level), reversing a five-year downward trend (U.S. DOE, 2010). In November 2010, the White House announced that the 2012 weapons budget would be further increased to $7.6 billion and that the total requested in FY 2012-2016 would be $41.6 billion (Public Law 111-84 Update, 2010). If passed by Congress and, more importantly, sustained in future years, this funding could assist in rebuilding critical technical capabilities. It will be important, however, to maintain effective control of the construction costs of major facilities to avoid the need to divert funds from stockpile stewardship.

A key step in sustaining the infrastructure is a clear policy statement of what is to be sustained. The Nuclear Posture Review (U.S. DOD, 2010a) concluded that "the following key investments are required to sustain a safe, secure, and effective nuclear arsenal:

- Strengthening the science, technology, and engineering …base…. This includes developing and sustaining high quality scientific staff and supporting computational and experimental capabilities.
- Funding the Chemistry and Metallurgy Research Replacement Project at Los Alamos National Laboratory to replace the existing 50-year-old Chemistry and Metallurgy Research facility in 2021.
- Developing a new Uranium Processing Facility at the Y-12 Plant in Oak Ridge, Tennessee to come on line for production in 2021."

More broadly, the Nuclear Posture Review (NPR) called for recapitalization of the nuclear infrastructure, including some modest capacity to surge production in response to geopolitical surprise (U.S. DOD, 2010a, pp. 42-43).

The committee endorses these policy goals. However, implementation will be crucial. The NPR calls for DOE/NNSA to develop a long-term strategy for science, technology, and engineering. It will be important for both the Administration and the Congress to reach consensus on this plan and to ensure its implementation thereafter.

Finding 3-2: A strong national commitment to recruiting and sustaining a high-quality workforce; recapitalizing aging infrastructure and force structure; and strengthening the science, engineering, and technology base is essential to sustaining a safe, secure, and reliable stockpile, as well as necessary explosion-monitoring capability for the United States.

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[3] NNSA anticipates that the greater efficiencies brought by the industrial partners in the new contracts will eventually compensate for these costs. This increased efficiency has not yet been demonstrated.

Recommendation 3-1: The Administration, in concert with Congress, should formulate and implement a comprehensive plan that provides a clear vision and strategy for maintaining the nation's nuclear deterrence capabilities and competencies, as recommended in the 2010 Nuclear Posture Review and related studies.

As noted in Chapter 1, to sustain a technically competent, motivated, and capable workforce, the U.S. nuclear weapons laboratories will need to employ some degree of innovation. DOE/NNSA and its contractors will need to take all of the traditional measures for recruiting and retaining high quality staff discussed above, but those are not sufficient. For example, doing a better job of involving nuclear capable personnel in related national security projects (e.g., nuclear forensics, intelligence, nonproliferation, threat reduction programs, and basic science application of stewardship facilities) can broaden the base of nuclear expertise, but such activities must be encouraged and supported by DOE/NNSA and laboratory management as well as Congress and the administration. There will always need to be a dedicated core of stewardship scientists, but the impact of the DOE national laboratories on the broader national security landscape can be enhanced while at the same time providing a larger and more diversified set of people able to contribute to nuclear enterprises. The DOE began moving in this direction with former Secretary Bodman's 2008 statement "Transforming the Nuclear Weapons Complex into a National Security Enterprise" (Bodman, 2008). DOE /NNSA should continue to pursue this vision. The committee also notes that maintaining a program of leading-edge science in the weapons labs can attract the scientific talent that will subsequently provide an internal source of expertise for the nuclear-weapon programs.

Implementing these ideas will require the full support of DOE and NNSA, which both place requirements on the nuclear weapons facilities. Each laboratory or plant has special circumstances, and one size does not fit all. What is important is to allow different sites to use different approaches (which will likely have different levels of success) without undue interference by either DOE or NNSA. In the committee's view, a bureaucratic structure that imposes overly prescriptive requirements does not maximize technical innovation and effectiveness.

Management Issues

Sustaining U.S. nuclear weapons programs requires adequate funding and a competent, motivated workforce, both discussed above. It also requires sound management of both fiscal and human resources. During this committee's investigations, we repeatedly learned of management issues that interfere with the ability to sustain the nuclear weapons enterprise. We summarize and discuss these problems in this section. Although we focus on the weapons laboratories, where the problems appear to be the most severe, we stress that sound management throughout the entire nuclear weapons enterprise in both the Departments of Defense and Energy is a prerequisite for long-term sustainability of the nuclear weapons program.

It is useful to review the history of how and why the current structure evolved. The nuclear weapons complex is under the authority of the NNSA, which was conceived as a semi-autonomous organization located within the DOE. Congress established NNSA in 2000 in response to a series of security problems and in the hope of improving the overall management of the nuclear weapons program. In the intervening years, several outside examinations have concluded that NNSA has not improved management of the nuclear enterprise to the degree its founders hoped and the nation requires. For example, the Congressional Commission on the Strategic Posture of the United States (2009) concluded that:

> The NNSA was formed to improve management of the weapons program and to shelter that program from what was perceived as a welter of confusing and contradictory DOE directives, policies, and procedures. Despite some success, the NNSA has failed to meet the hopes of its founders. Indeed, it may have become part of the problem, adopting the same micromanagement and unnecessary and obtrusive oversight that it was created to eliminate.[4]

Similar conclusions were reached by the Defense Science Board (DSB, 2006, pp. 29-30), and a study conducted by the Henry L. Stimson Center (Task Force, 2009). Each of these reports concluded that the problem was likely to remain unless NNSA were moved from the Department of Energy but that it still should remain independent of the Department of Defense. In addition, the Congressional Commission on the Strategic Posture of the United States concluded that NNSA needs to change its approach to oversight and management radically. The Commission noted that although the NNSA has authority for the nuclear weapons facilities, DOE independently imposes its health, safety, and security requirements.[5]

Management concerns are paralleled by the disturbing trend of reducing resources needed for the technical mission of the laboratories, which is amplified by the Performance Evaluation Plans used by NNSA to manage the contracts for the sites in the nuclear weapons complex. In reality the historical model of Government-Owned, Contractor-Operated (GOCO) laboratories has become Government-Owned, “Contract”-Operated, where both the day-to-day management and the incentives are driven almost entirely by the fine print of the contract and its implications for the fees of the contractors.

In Boxes 3-1 and 3-2 below, we contrast management approaches in nuclear weapons laboratories in the United States and the United Kingdom.

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[4] Details of the Commission’s concerns and proposed solutions are found on pages 55-62 of the Commission’s report.

[5] In addition, the Defense Nuclear Facilities Safety Board makes its own recommendations to DOE that can have a direct impact on how time and resources are allocated.

BOX 3-1 An Example of the Current Management Approach to the U.S. Nuclear Weapons Laboratories: The FY 2009 Plan for the Los Alamos National Laboratory Contract

The contract involves a fee structure with a fixed base fee and a larger incentive fee determined by a Performance Evaluation Plan (PEP). This committee reviewed the PEP and found it unbalanced in its focus. The PEP defines 18 Performance-Based Initiatives (PBIs) with 100 pages of description, much of which includes very rigidly defined deliverables. Of these 18 PBIs, only three (Multi-site Performance, Threat Reduction, Science and Mission Excellence) actually address the technical mission of the laboratory. As a result, the technical mission of the laboratories is incentivized by less than one-third of the at-risk fee. All the remaining PBIs address operational issues and business and management procedures. The descriptions of the operational and business PBIs glaringly lack incentives designed to measure the effectiveness of their support for the technical mission. Instead, the specific metrics focus on internally referential activities such as completing paperwork correctly, holding meetings on a prescribed schedule, or providing reports by a specific date. Overall, the PEP strikingly demonstrates the antithesis of the recommendation of the recent Congressional Commission (2009) that the management of the nuclear complex should involve government definition of the goals, with contractor responsibility for determining the best methods of reaching those goals. An alternative management approach embodying this principle is described in Box 3-2.

BOX 3-2 An Alternative Management Approach

The committee’s judgment on the damaging impact of the present rigidity of the nuclear weapon laboratory governance, funding, and direction was reinforced by interviews and a presentation on the United Kingdom’s nuclear weapon program centered at Atomic Weapons Establishment (AWE) Aldermaston and AWE Burghfield and funded by the UK Ministry of Defence (MOD). The AWE is run as a government-owned, contractor-operated facility under the MOD. The United Kingdom experienced similar problems to those discussed above when it established a system very like the PEPs, but has been able to work toward a more effective system. The UK analog of the PEP is a System Requirements Document that describes the work MOD wants done by AWE. In 2006, the System Requirements Document had more than 650 items, with about half being related to safety and security, and less than half devoted to the technical requirements. Moreover, many of the requirements addressed "how" the technical work and safety/security tasks were to be done rather than specifying the goals. In short, there was more emphasis on the "how" than the "what" and this was clearly not optimal.

Recognizing the dysfunction of such an approach, AWE and MOD systematically worked to 1) reduce the number of requirements in the System Requirements Document; 2) improve the requirements balance by focusing 80 percent of the requirements on the technical work with 20 percent of the requirements focused on safety/security; and 3) increase the focus on specifying "what" work was required, but decrease or eliminate the focus on specifying "how" the work was to be achieved.

After two years, the number of requirements in the System Requirements Document was cut nearly in half, with the focus on goals, and an improved technical/non-technical balance. To achieve MOD support of this change, AWE agreed to work to a set of milestones (annual and 5-year) under a fully incentivized program. AWE was able to use the promise of a multi-year funding commitment to attract and build technical capability among the staff. It also placed more accountability with the staff at lower levels because they were in the best position to make the technical and safety/security advances. After a number of years of operation, it appears to the committee that this “eyes on, hands off” approach is performing well.

This revised management approach provides significant opportunities to address the endemic workforce problems described in the text. Allowing the workforce to have the technical responsibility and flexibility in defining the paths to mission goals supports both workforce development and workforce morale. The "challenge programs" run by the AWE illustrate what can be achieved in this regard. For example, in one challenge program the AWE designed a new warhead (together with the non-nuclear components), although the UK has no intention of producing any such weapon. This helped to maintain proficiency and train the next generation of warhead designers. Such flexibility for activities undertaken by AWE with MOD approval (but not MOD direction) helps to recruit and maintain a top-flight workforce and to exercise the advanced tools of the program. Programs of this nature have been tried, with positive workforce response, in the U.S. complex, but have fallen victim to budget pressures and micromanagement to short-term goals.

Finding 3-3: The current contract system for the nuclear weapons laboratories has not produced a more innovative, efficient, and cost-effective approach to carrying out the tasks of the nuclear weapons program. Rather, there is evidence that the present system acts as a significant barrier to many of the objectives delineated in this report.

Recommendation 3-2: The DOE/NNSA should re-evaluate the current contract system for carrying out the tasks of the nuclear weapons program. At a minimum, any new approach should:

- **Reduce the number of requirements in directives and simultaneously transform those requirements to performance goals (prescribing what must be done, not how to do it).**
- **Shift the balance of incentives in contracts for the weapons laboratories to emphasize successful implementation of the technical mission.**

SUSTAINING U.S. MONITORING CAPABILITIES

Chapter 2 summarizes the major improvements in U.S. and international technical monitoring capabilities achieved since 2000. Though impressive, continuing improvements in monitoring technology for treaty verification and related field procedures are needed to stay ahead of possible evasion attempts by proliferators. Investments in government sponsored monitoring technology research at laboratories and universities are important for keeping pace with the evolving international environment. The need to maintain these capabilities is not dependent upon whether the United States ratifies the CTBT. Rather, these are capabilities that the United States has maintained and will need to maintain in the future for its own security. Attention to priorities and investments across the programs supporting research and development in this area would help to maintain cutting edge technical monitoring capabilities.

Specific issues needing attention are:

- *Access to skilled personnel.* This is also discussed in the section above on the workforce needed to sustain the nuclear weapons program. Two additional points are relevant in the context of sustaining monitoring and verification capabilities. First, assessments of potential adversary actions such as possible evasion scenarios rely on some of the same skilled nuclear weapon personnel at the national labs as the nuclear weapons program. Some of these same personnel also participate in cooperative and transparency measures through bilateral technical exchanges that complement technical monitoring. The second point is that the development of new monitoring technology requires scientists with post-graduate training in fields such as radiochemistry, seismology, geophysics, and atmospheric and space sciences. Few university research and training programs include applications of science to treaty monitoring, making it difficult to engage students in this field early in their careers.

- *Access to research facilities.* National security programs, including treaty monitoring and verification, need access to the unique computational and experimental facilities at the national labs. This access must be balanced across the needs of intelligence, defense, and science, as well as the nuclear weapons program.
- *Access by agencies other than DOE/NNSA.* Access by other agencies to unique national lab expertise and facilities has traditionally been via the work-for-others process (basically consisting of piecemeal interagency job orders). The committee supports the findings of previous studies that access to these capabilities and expertise by other U.S. agencies should be on a more equal footing (Congressional Commission, 2009; Task Force, 2009). At the same time, other agencies should help maintain these national capabilities through infrastructure investment.

A governance charter that addresses support by the national laboratories to the national security missions of other government agencies, and the mutual responsibility for sustaining the laboratories' capabilities, has recently been signed by the Director of National Intelligence and the Secretaries of Energy, Defense, and Homeland Security (Governance Charter, 2010). It is too early to tell whether this will make a difference.

Finding 3-4: Technical improvements needed for monitoring the CTBT (and other treaties) would benefit greatly from better access to skilled personnel and computational and experimental facilities at the national labs. This access is needed by agencies with CTBT monitoring and verification responsibilities.

Recommendation 3-3: Provisions of a recently-agreed-to governance charter should be implemented to enable better access to skilled personnel and capabilities at the national labs by agencies other than DOE/NNSA. Such access will directly benefit research and technology development aimed at improving CTBT (and other treaty) monitoring and verification. A model plan should be developed that encourages and enables investment in DOE/NNSA facilities by agencies that benefit from access to these facilities. Such a strategy would help ensure adequate and properly sized infrastructure to support SSP, international treaty monitoring and verification, and national security programs.

U.S. Government Investments

As noted above, the technologies that support treaty monitoring require continuing infusion of the latest science and technology. This is accomplished through major investments at the national laboratories and in industry, which provide the core, sustaining technology development and transfer to the operators of the monitoring systems, as well as through investments at universities to train new talent. The source of these investments is almost exclusively the U.S. government.

Department of Defense

Within the Department of Defense, the Assistant Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs (ASD/NCB) plays a major role of oversight and coordination. The Nuclear Arms Control Technology (NACT) program is overseen by this office and is carried out by the Army Space and Missile Defense Command (SMDC). Since 2003, this program has been responsible for the acquisition, installation, operation, and maintenance of part of the U.S. contribution to the IMS monitoring system, including the 37 U.S. IMS stations (17 seismic, 11 radionuclide, 1 hydroacoustic, and 8 infrasound stations). The cost of the NACT program since 2003 has been approximately twenty million dollars ($20M) per year for 24/7 operation of the stations, including $3-6M annually for research, development, test, and evaluation of the supporting technology. The committee has been advised that the current level of funding will be inadequate to support operations and maintenance of the U.S. IMS monitoring stations following entry into force of the CTBT.

Specialized work in the 1970s and 1980s needed to estimate the yields of large Soviet underground nuclear explosions using teleseismic signals was supported by R&D programs typically at the level of $15M annually for projects submitted by academia and industry. Today, the work of monitoring for CTBT compliance globally is far more complicated than was the case in the era of large-yield testing at a few known nuclear-explosion test sites, because vastly greater areas now have to be monitored, and the analysis has to be done down to much smaller seismic magnitudes using far more stations, leading to the need to study numerous earthquake signals on a daily basis. But the R&D programs supporting the operational work in recent years have been much smaller than in previous decades. For example, the Air Force Research Laboratory (AFRL) Explosion Monitoring R&D Program funding history in recent years is shown in Table 3-1.

TABLE 3-1: Baseline Investments in the Research Community by the AFRL Nuclear Explosion Monitoring (NEM) Seismic Research Program, FY 2003-FY 2011.

Fiscal Year	**Appropriated ($Ms)**	**Baseline University Contracts**	**Congressional Add-Ons for University Contracts ($Ms)**	**Total University Contracts**	**Total Funding**
2003	4.0	4.0	3.0	7.0	7.0
2004	6.62	4.74	0	4.74	6.62
2005	7.05	4.95	2.8	7.75	9.85
2006	6.98	4.74	0	4.74	6.98
2007	6.86	4.64	0	4.64	6.86
2008	6.82	4.55	2.4	6.95	9.22
2009	6.81	4.51	2.0	6.51	8.81
2010	6.11	3.02	5.0	8.02	11.11
2011	6.35	3.13	0	3.13	6.35

SOURCE: Adapted from Air Force Research Laboratory

This explosion-monitoring R&D program, managed for more than a decade at Hanscom Air Force base in Massachusetts as a small component of AFRL's Space Technology Program has recently moved to Kirtland Air Force Base in New Mexico. It is the only DOD seismic-research monitoring program that supports the Air Force's nuclear-test treaty-monitoring mission.

Finding 3-5: Air Force Research Laboratory (AFRL) funding for nuclear explosion-monitoring R&D is significantly lower than in past decades, whereas the monitoring task has become far more complicated.

Recommendation 3-4: For the United States to monitor effectively for the possibility of nuclear-test explosions, the U.S. Government should fund a robust R&D program to maintain ongoing operational capabilities and to support achievable improvements.

As the operator of the USAEDS, AFTAC needs continued access to highly trained and experienced technical experts in treaty monitoring and to advanced technologies and systems. Notable accomplishments and enhancements of the USAEDS were made over the past decade in all aspects of nuclear explosion monitoring. (See Chapter 2 for further information.) However, effective monitoring of the CTBT requires continued R&D investment and transfer of the resulting improved monitoring capabilities to the USAEDS. (CTBT monitoring challenges are discussed in Chapter 4.) Research at universities is vital for advancing treaty monitoring and for mentoring new generations of scientists and engineers to make careers in this field. Research at universities is vital for advancing treaty monitoring and for mentoring new generations of scientists and engineers to make careers in this field. As discussed below, investments in treaty-related research at universities have fluctuated dramatically and unpredictably, which undermines the programs and their ability to provide the research results.

Finding 3-6: Continued enhancement of the USAEDS is necessary to monitor the CTBT. Research and development of advanced monitoring capabilities are needed, including research and training at universities of the next generation of scientists and engineers.

Recommendation 3-5: A sustained, predictable program of investment in nuclear-explosion monitoring R&D should be coordinated among the responsible U.S. agencies. This program should specifically include investments in university research and training programs focused on technical disciplines critical for treaty monitoring.

Within the DOD, the Defense Threat Reduction Agency (DTRA) and its predecessor, the Defense Nuclear Agency (DNA), have traditionally had lead responsibility for treaty verification R&D. Attention to this responsibility has dwindled over the past decade.

Department of Energy/National Nuclear Security Administration

Through its Office of Nonproliferation & Verification Research & Development (NA-22), the DOE/NNSA has, over the past decade, continued to support treaty verification R&D at levels above $100M per year. Virtually all of this is invested at the national labs to develop and transfer technology to enhance the USAEDS. This program has had significant successes as indicated by the enhancements to USAEDS capabilities described in Chapter 2.

Investments in treaty monitoring by DOE/NNSA over the past decade are shown in Figures 3-1 and 3-2. Figure 3-1 shows investments in the DOE/NNSA Ground-based Nuclear Explosion Monitoring (GNEM) program, which consists of three elements: (1) Broad Agency Announcements (BAAs, including university contracts administered jointly with AFRL), (2) waveform (seismic, infrasound, and hydroacoustic) science and data integration, and (3) radionuclide science. Total funding for the GNEM program has fluctuated up to 30 percent year to year. Because AFTAC relies on this program as a major source of new monitoring science and technology, the lack of predictable GNEM funding has made planning for monitoring system upgrades more difficult. Over the past decade, funding for university BAAs has fluctuated from $1 million to almost $7 million annually (see Figure 3-1). Such unpredictability negatively impacts university research and training programs.

Finding 3-7: Year-to-year funding for the Ground-Based Nuclear Explosion Monitoring (GNEM) R&D program has decreased in recent years. The decline of funding for university research is jeopardizing R&D and training of the next generation of researchers.

Recommendation 3-6: The DOE/NNSA Ground-Based Nuclear Explosion Monitoring (GNEM) Program merits sustained, predictable funding, including funding for university investments through a competitive, peer-reviewed process.

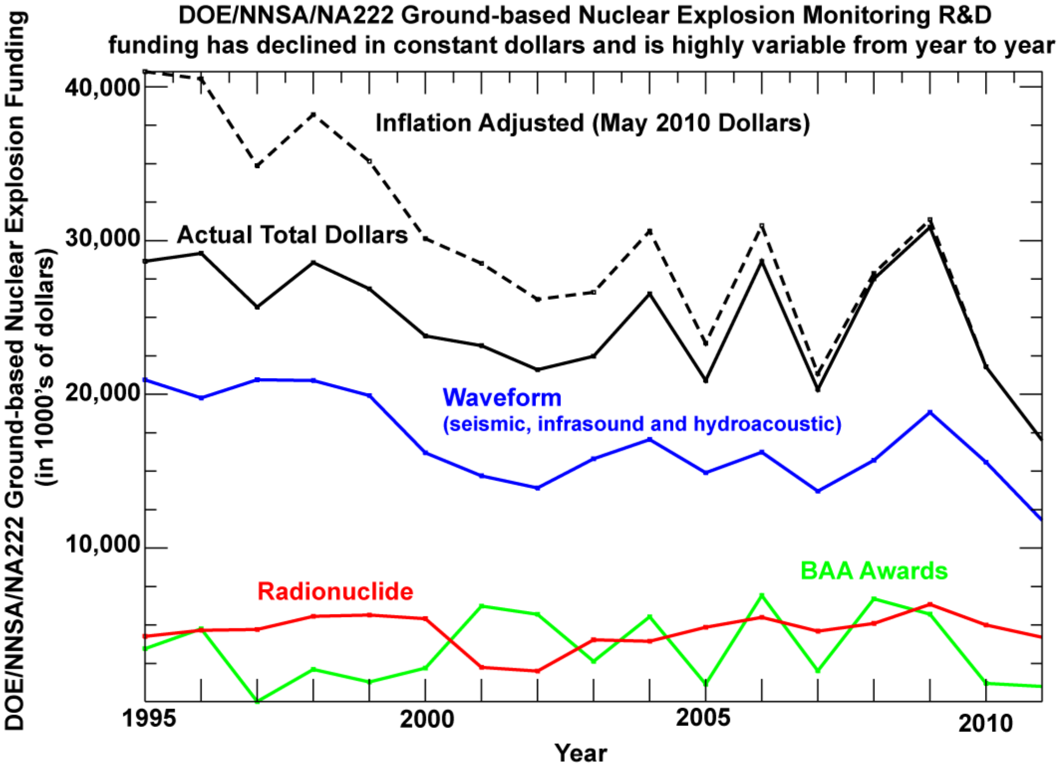

FIGURE 3-1: DOE/NNSA/NA-222 Ground-based Nuclear Explosion Monitoring R&D program has declined in constant dollars and is highly variable from year to year.
SOURCE: William Walter, Seismology Subcommittee member

The DOE/NNSA and the U.S. Air Force jointly carry out the satellite-based nuclear detonation detection system (USNDS). DOE/NNSA and the national labs provide the detection sensors and supporting data analysis while the Air Force provides the satellite platforms and data downlinks. Figure 3-2 shows the USNDS funding from 2000 through 2010. The DOE/NNSA NDS program consists of two components, detection systems (sensors and data analysis) and advanced technology development. In Figure 3-2, the Air Force costs to support the NDS mission are shown separately. The ability to adequately monitor the CTBT through 2020 and beyond requires that these joint investments continue, for example, to complete planned enhancements to the NDS on GPS satellites (Blocks IIF and III). (See Chapter 2 and Appendices G and H for a more complete discussion of the U.S. satellite monitoring capability.)

Finding 3-8: Planned enhancements to the U.S. satellite nuclear detonation detection capability are necessary to adequately monitor the CTBT. Even without the CTBT, these enhancements to the USNDS capability are important to maintaining and improving the USAEDS.

Recommendation 3-7: The DOE/NNSA and the U.S. Air Force joint satellite-based monitoring program (USNDS) should continue planned enhancements needed to monitor the CTBT through 2020 and beyond. Advanced technology R&D should continue to enable future enhancements and anticipate surprise.

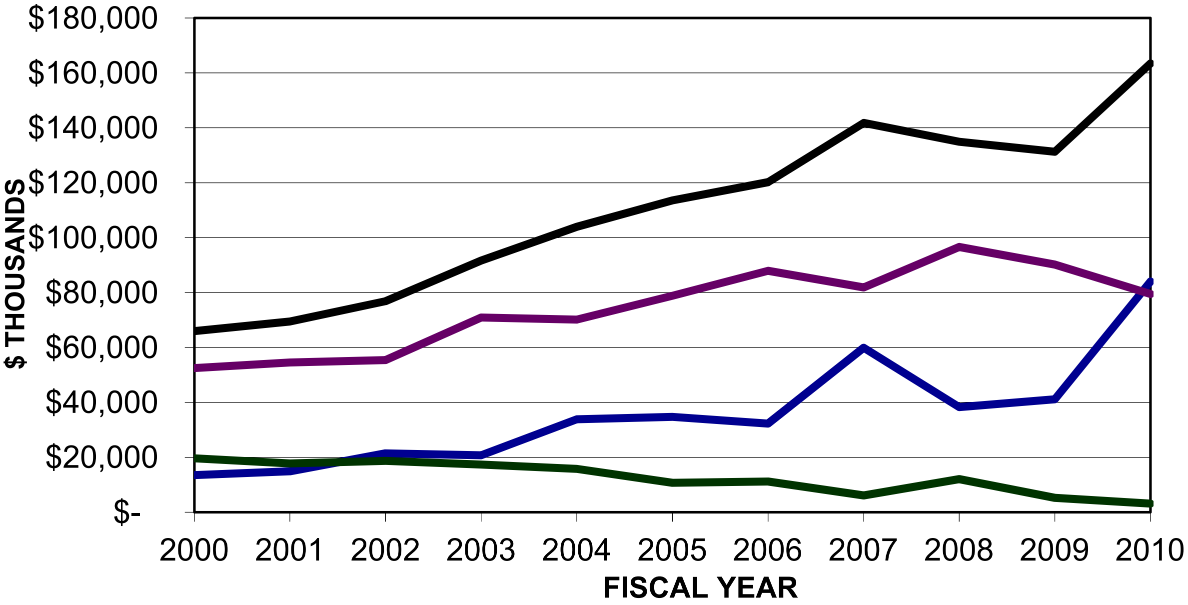

FIGURE 3-2: Funding history (2000-2010) of the U.S. Nuclear Detection System (USNDS) (satellite monitoring) including both DOE/NNSA and Air Force components.
Legend: DOE/NNSA NDS technology development (Green, bottom line); Air Force NDS support (Blue, second line); DOE/NNSA NDS sensors and systems (Purple, third line); Total USNDS (Black, top line). SOURCE: Committee

Director of National Intelligence

One funding source that stands out for its breadth and willingness to invest in both basic and applied R&D is the Intelligence-Advanced Research Projects Agency (I-ARPA). The committee applauds this new program instituted over the past decade. The committee also notes the recent memorandum of understanding signed by the DOE Secretary and the Director of National Intelligence and hopes that this portends a long-term, mutually supportive relationship between DOE/NNSA and the other U.S. national security agencies.

SUSTAINABILITY OF THE INTERNATIONAL MONITORING REGIME, INCLUDING ON-SITE INSPECTION

The United States has an interest in sustaining the CTBTO monitoring capability, especially the IMS. As noted in Chapter 2, IMS provides reliable, high-quality, authenticated data that complements data provided by NTM. If the United States were to lose access to the data from IMS stations that are integrated into the USAEDS monitoring network, this would reduce the flow of data to the United States.

A central function of the CTBTO is to complete the monitoring network defined under the Treaty. Based on information received in late 2009 from the CTBTO, the remaining capital costs needed to complete the IMS network are estimated at $355 million to complete the 321-station network that will consist of 50 primary seismic stations, 120 auxiliary seismic stations, 11 hydroacoustic stations, 60 infrasound stations, and 80 radionuclide stations, as well as 16 radionuclide laboratories. In addition, the costs of maintaining the network, called Post Certification Activities (PCA), were approximately $16 million in 2009 and covered activities at 125 stations and 9 radionuclide laboratories. Further, an average of about $12.6 million a year is spent on end-of-life replacements of equipment, necessary and often unanticipated station improvements, long-term maintenance, and any engineering and design work needed to mitigate possible station failure. Operating costs will increase when the full monitoring system is in place.

Under the assumption of a flat budget, it is estimated that it would take three years to complete over 90 percent of the IMS network while maintaining operations at the present level.

Finding 3-9: The current budget for the IMS allows operating its stations on a 24/7 basis; however, the stations are operating on a provisional basis, without weekend and emergency support contracts. The International Data Centre (IDC), now staffed for a limited number of hours each weekday, would have to move to 24/7 operation under CTBT entry into force.

Recommendation 3-8: The United States should support the CTBTO in its annual assessed and voluntary contributions to ensure that the IMS is fully installed and, with the IDC, is ready to meet CTBT entry-into-force obligations, including support for operating costs and long-term maintenance and repair of monitoring stations.

On-Site Inspection (OSI) Readiness

The OSI capability of the CTBTO lags behind the readiness of the IMS for entry into force. Substantial additional resources will be needed to prepare the CTBTO to implement a full on-site inspection capability. Important lessons were learned from the 2008; Integrated Field Exercise (IFE) that have been documented by the CTBTO PTS (CTBTO, 2008; VERTIC, 2008). In the committee's discussions with CTBTO staff, it was told that the IFE cost approximately $7 million but that the actual cost of a real OSI will be highly dependent on the locations of the inspection area and base of operations. CTBTO staff expects that for a real inspection, there would be higher costs for transportation of both inspectors and equipment. For the 2008 IFE, 50 tons of equipment was shipped to Kazakhstan, but the exercise was not designed to include all inspection technologies available to inspectors under an actual OSI. Under real circumstances, the timeframe for organizing an inspection will be much tighter than was the case for the IFE, which also may drive up costs.

Finding 3-10: The OSI capability of the CTBTO lags behind the readiness of the IMS; however, steps have been taken, such as the 2008 Integrated Field Exercise, which have improved OSI capabilities significantly.

Recommendation 3-9: The United States should support the CTBTO OSI work by participating fully in all of its aspects, including training and field exercises.

CTBT SAFEGUARDS

The provision of safeguards is common in arms control treaties as a device to mitigate any perceived risks of ratifying the specific treaty and thereby constraining future U.S. options. Safeguards are typically proposed by the administration and adopted by the Senate, often after considerable negotiation, both internally and with the White House. By including appropriate safeguards in the resolution giving advice and consent to ratification, the Senate makes its approval contingent on the expectation of sustained implementation of specific actions over the life of the treaty.

Proposed Clinton Administration Safeguards

When President Clinton announced U.S. support for a "zero yield" CTBT on August 11, 1995, he established six specific safeguards (listed in Box 3-3) that were included in his formal transmittal of the Treaty on September 22, 1997, to the Senate for its advice and consent to ratification.

Presumably, these safeguards will serve as the basis for the safeguards that the current Administration will propose, and the committee would support this action. Because the Administration is now considering how to revise the 1997 safeguards, the committee has not sought to provide specific text. Instead, it has considered the technical adequacy of the 1997 safeguards in light of developments over the past decade. It has also examined the question of whether whatever safeguards are ultimately adopted can be sustained over time.[6]

BOX 3-3 Safeguards Proposed in 1995

A) The conduct of a Science-Based Stockpile Stewardship program to ensure a high level of confidence in the safety and reliability of nuclear weapons in the active stockpile, including the conduct of a broad range of effective and continuing experimental programs.

B) The maintenance of modern nuclear laboratory facilities and programs in theoretical and exploratory nuclear technology that will attract, retain, and ensure the continued application of our human scientific resources to those programs on which continued progress in nuclear technology depends.

C) The maintenance of the basic capability to resume nuclear test activities prohibited by the CTBT should the United States cease to be bound to adhere to this Treaty.

D) The continuation of a comprehensive research and development program to improve our Treaty monitoring capabilities and operations.

E) The continuing development of a broad range of intelligence gathering and analytical capabilities and operations to ensure accurate and comprehensive information on worldwide nuclear arsenals, nuclear weapons development programs, and related nuclear programs.

F) The understanding that if the President of the United States is informed by the Secretary of Defense and the Secretary of Energy (DOE)—advised by the Nuclear Weapons Council, the

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[6] By mutual consent of Congresses and Administrations, Safeguard C (test readiness) has not been fully implemented.

Directors of DOE's nuclear weapons laboratories, and the Commander of U.S. Strategic Command—that a high level of confidence in the safety or reliability of a nuclear weapon type that the two Secretaries consider to be critical to our nuclear deterrent could no longer be certified, the President, in consultation with the Congress, would be prepared to withdraw from the CTBT under the standard "supreme national interests" clause in order to conduct whatever testing might be required.[7]

New or Modified Safeguards

The safeguards listed in Box 3-3 make no mention of nuclear weapon production capabilities, but maintaining agile production[8] capabilities as a complement to the SSP is essential to the long-term health of the nuclear stockpile. This leads to the following finding and recommendation.

Finding 3-11: Without agile production capabilities, it is not possible to promptly correct deficiencies revealed by surveillance or to remanufacture components or weapons when required.

Recommendation 3-10: The U.S. CTBT safeguards should include the maintenance of adequate production and non-nuclear-explosion testing facilities.

Of concern also is the question of whether the safeguards will achieve their purpose of ensuring appropriate future action. There are at least three problems in relying on safeguards. First, most require sustained funding and thus require support by the House of Representatives, which is not directly involved in the ratification process. Second, safeguards are typically very general, allowing differing interpretations of whether a future administration is complying with them. Finally, there is no legal enforcement mechanism should a future administration elect not to adhere to safeguards in detail because of competing budgetary priorities or changing policy preferences.

Uncertainty over the future implementation of safeguards is inherent in the U.S. political process. Given this fact, the committee judges that it is both appropriate and necessary for the United States to periodically conduct a formal review of whether safeguards remain effective. The committee is impressed with the utility of the annual stockpile assessment letters prepared by the three weapons laboratory directors and the Commander of U.S. Strategic Command and provided to both the President and the Congress. It seems reasonable that a similar approach could be defined regarding safeguards.

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[7] CTBT Article IX (in paragraphs 2 and 3) states “Each State Party shall, in exercising its national sovereignty, have the right to withdraw from this Treaty if it decides that extraordinary events related to the subject matter of this Treaty have jeopardized its supreme interests. Withdrawal shall be effected by giving notice six months in advance…Notice of withdrawal shall include a statement of the extraordinary event or events which a State Party regards as jeopardizing its supreme interests.” Provisions allowing withdrawal under a *supreme interests* provision (also commonly referred to as *supreme national interests*) are common in arms control agreements, e.g., the Chemical Weapons Convention [Article XVI], the INF Treaty [Article XV], START [Article XVII(3)], the Non-Proliferation Treaty [Article X], and the ABM Treaty [Article XV]. The United States used the provisions of Article XV in withdrawing from the ABM Treaty in 2002. The ability to withdraw from a treaty is the ultimate safeguard and could be exercised if the United States ever concluded that its national security required it to resume nuclear testing.

[8] By *agile production* we mean the ability to produce any components of any of the stockpiled designs in quantities and on timescales needed to respond to stockpile problems.

Finding 3-12: There is currently no mechanism that would enable Congress to assess whether the U.S. CTBT safeguards were being fulfilled after entry into force.

Recommendation 3-11: Under the CTBT, the Administration should prepare an annual evaluation of the ongoing effectiveness of safeguards and formally transmit it to Congress.

This annual report by the President of the United States should be comparable in detail to the annual stockpile assessment letters and should be informed by the Secretary of Defense, Secretary of Energy, and the Director of National Intelligence and should be advised by the Nuclear Weapons Council, the directors of the appropriate national laboratories, the Committee of Principals established under National Security Presidential Directive-28 (NSPD-28)[9] and the Commander of U.S. Strategic Command. This would both ensure a routine internal review of the status of safeguards and provide a mechanism for Congressional oversight. The provision of such a detailed report would help compensate for the general nature of the safeguards. Some observers advocate devising specific metrics for safeguards to provide a degree of objectivity to these annual assessments.[10] The committee concludes that, although specification of metrics is a level of detail inappropriate for the formal safeguards themselves, such metrics might provide a valuable tool for those charged with preparing annual assessments. Great caution would be required to devise metrics detailed enough to provide an objective standard without degenerating either into a welter of data of limited value to senior leaders or replacing real technical assessment with paperwork micromanagement as discussed above in the management context.

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[9] NSPD-28, *U.S. Nuclear Weapons Command and Control, Safety and Security*, establishes a Committee of Principals to coordinate issues associated with nuclear command and control, safety, and security. The broad participation of relevant agencies in the Committee of Principals makes it appropriate to seek their advice on the ongoing efficacy of the CTBT safeguards.

[10] For additional details on metrics, as well as a discussion of the history of safeguards, see Medalia (2009).

4

POTENTIAL TECHNICAL ADVANCES FROM NUCLEAR-EXPLOSION TESTING

The CTBT would make it illegal for signatory nations to conduct nuclear-explosion tests. Its effectiveness would depend on both the technical means available for detecting violations and the commitment to its enforcement by the parties involved. As discussed in Chapter 2, the ability to detect nuclear weapons tests has advanced substantially in the past 10 years, creating increased difficulties for clandestine nuclear weapons programs. However, assessing the potential threats to U.S. national security that undetected nuclear-explosion testing might pose is an important component of the discussion concerning U.S. ratification of the CTBT. Alternative threats to U.S. national security from resumption of full-yield nuclear-explosion testing must also be considered.

Since the *2002 Report,* the issues regarding the security implications of the CTBT have changed substantially in some areas and little in other areas. In the following, we will address some key points where changes have occurred or where the committee concludes that clarification is needed. These specifically include changes in the nuclear programs of other NPT-acknowledged Nuclear Weapon States, the lack of a definition of "nuclear explosion" in the CTBT text, the probability of detection, the implications for those hoping to avoid detection, and the feasibility of evasion for avoiding detection. With those basics established, we update the comparison used in the *2002 Report* of the potential threats posed by ratification of the CTBT given the possibility of clandestine tests versus the threats posed by a possible return to global full-yield nuclear-explosion testing.

OVERVIEW AND *2002 REPORT* FINDINGS

The *2002 Report* found that "taking all factors into account and assuming a fully functional IMS," an evasively-tested nuclear explosion could not "be confidently hidden if its yield is larger than 1 or 2 kilotons" (NRC, 2002*,* pp. 7, 48). Two methods of evasive nuclear-explosion testing—mine masking and cavity decoupling—were judged to be potentially effective and were included in the prior assessment. The report concluded that Russia and China, with their substantial prior testing experience, would be in the best position to carry out a successful evasive test. The *2002 Report* concluded that Russia and China would be able to extract useful results from low-yield evasive testing, but these would add little to the threat they already posed to the United States (NRC, 2002, pp. 70-73).

In contrast with the cases of Russia and China, the *2002 Report* concluded that States with less prior test experience and/or design sophistication are much less likely to succeed in concealing significant nuclear explosion tests. Although low-yield or evasive testing might help lay the groundwork for a future nuclear weapons program, it would not enable mastery of nuclear weapons more advanced than the ones that they could develop and deploy without any testing at all.

CHANGES SINCE THE *2002 REPORT*

Since the *2002 Report,* the United States and other Nuclear Weapon States have shown that they can maintain their nuclear arsenals and, in the cases of Russia and China, modernize them under a testing moratorium.

Advances in monitoring technology and capability since the *2002 Report* (discussed in Chapter 2) have only made the prospect of evasive nuclear explosion testing more challenging.

The committee judges that, in addition to testing below detection levels, only two other evasion measures, mine masking and cavity decoupling, warrant serious discussion. The committee found no evidence of any new technical developments that would facilitate these evasion scenarios. The use of mine masking as an evasion strategy is challenging because the seismic monitoring of mining regions has improved and because the limitations of mine masking are better understood. With regard to decoupling as an evasion strategy, there is little new technical information since the *2002 Report*. The challenges described in that report to a would-be evader attempting to decouple the seismic signal remain pertinent today. A more detailed technical discussion of evasive testing is presented in Appendix E.

NUCLEAR WEAPON STATES (NWS) PROGRAMS UNDER A TEST MORATORIUM

It is important to be clear about what will and will not be technically affected by the CTBT. The CTBT bans nuclear-explosion testing but does not proscribe other activities for maintaining or even expanding a State's overall nuclear capabilities. As a result, the United States has been able to sustain its nuclear stockpile under the test moratorium that has been in effect for nearly two decades, and to develop science-based tools that ensure the capability to use the results of the substantial U.S. test history in future work on nuclear weapons. It is reasonable to expect (and indeed the record shows) that other advanced weapons States will also use science-based approaches in maintaining and possibly adapting their nuclear weapons. Such activities may be quite extensive, but under a test ban, weapons deployable with confidence will be limited to designs that fall within the range of previously tested designs.[1]

Here we present a synopsis of how the four other Nuclear Weapon States (NWS) under the NPT are maintaining and to some extent modernizing their stockpiles of nuclear warheads and delivery systems. Among these four States, Russia has nearly an order of magnitude more nuclear warheads than the United Kingdom, France, and China combined. Of the four countries, Russia, the United Kingdom and France have signed and ratified the CTBT; like the United States, China has signed but has not yet ratified.

Russia

Efforts to modernize and reform Russia's Armed Forces have been ongoing for most of the period following the end of the Soviet Union. The role and structure of Russia's nuclear arsenal have been part of these general military modernization efforts. Russia continues to maintain its national nuclear weapon design laboratories at Sarov and Snezhinsk and to upgrade research facilities in line with a SSP-like program to maintain its nuclear stockpile. Russia also continues to maintain an active production complex.

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[1] There is also the possibility of acquiring information through espionage or transfer, but that is beyond the scope of this report.

Nuclear Test Site

When the Soviet Union ratified the Threshold Test Ban Treaty with the United States in 1990, it declared two official sites for testing nuclear weapons—eastern Kazakhstan (Semipalatinsk) and the island of Novaya Zemlya (Mikhailov, 1996). The former was the primary location for Soviet nuclear-explosion tests from 1949 to 1989 (Adushkin and Leith, 2001) and was closed in 1989. The largest Soviet underground nuclear-explosion tests, however, were conducted at two sites on remote Novaya Zemlya, one of which (the Krasino site on southern Novaya Zemlya) has not been used for testing since 1975. Russia continued testing at its Arctic test site near Matochkin Strait on Novaya Zemlya until 1990 (Khalturin et al., 2005). The Russian nuclear-explosion test site at Novaya Zemlya is now the site of ongoing experiments termed *hydrodynamic* by Russian spokesmen. Truly hydrodynamic tests have no nuclear explosive yield and thus are, by definition, compliant with the CTBT. However, there is some dispute about whether Russia considers certain nuclear tests (hydronuclear) with very low yields (up to 100 kg—see the section below on “Hydronuclear Testing”) to be compliant with the CTBT. In the absence of access to the test site, it is impossible to determine by physical means whether or not the ongoing activities at Novaya Zemlya include such very-low-yield tests.

Modernization Efforts

Russian President Dmitry Medvedev announced the latest plans for strategic force modernization on March 17, 2009. The 2009 budget allocated 1.5 trillion rubles (about $45 billion), with approximately $12 billion directed toward strategic nuclear forces (Perfilyev, 2009). In February 2010, President Medvedev approved the new military doctrine, “Principles of the State Policy of Nuclear Deterrence until 2020”; this is largely consistent with the previous Russian doctrines released in 1993 and 2000.

As of September 2011, Russia deploys 516 ICBMs, SLBMs, and Heavy Bombers. The New START treaty verification regime counts 1,566 Russian warheads on Deployed ICBMs, SLBMs and Heavy Bombers (U.S. Department of State, 2011a). The New START Treaty limits strategic delivery vehicles to 800, including up to 700 actively deployed and 100 in maintenance or refitting. New START limits the total number of deployed strategic warheads and bombs to 1,550. It is unclear whether the new Treaty will change how Russia structures its land based strategic missile force; the limits would not appear to require a major restructuring.

Although further nuclear arms reductions are foreseen by Russia’s military leadership, they seek to qualitatively transform the strategic forces through life extension programs and new, enhanced long-range missile systems (*RIA Novosti*, 2009). Russia is reported to deploy 376 intercontinental ballistic missiles (ICBMs) (Nichol, 2011). Russia is slowly replacing its older Soviet-era ICBMs (SS-18 and SS-19) with new ICBMs, including missiles derived from the solid-fueled Topol series. Russia plans to replace these systems by 2022 and is now deploying a modernized version called the Topol-M (SS-27), designed to improve performance against ballistic missile defense, and plans to deploy a MIRVed version of the Topol-M (Perfilyev, 2009). Russia is also reported to be developing a next-generation liquid-fueled heavy ICBM (GSN, 2011).

Improvements to its nuclear-powered ballistic missile submarines (SSBNs) are also being introduced by the Russian navy. “The sea-based leg of the nuclear triad will consist of six Project 667BDRM Delfin (Delta IV) submarines with R-29RM Sineva missiles, which will gradually be replaced by up to eight Project 955 Borey submarines with Bulava missiles…” (Perfilyev, 2009). However, these deployments have been delayed by failed tests and other technical difficulties. At present, only a single Borey class submarine is operational (although without missiles), with two more under construction (*Russian Forces*, 2010). According to Russian Navy officials, "The modernized Borey will be the core of Russian naval nuclear forces until 2040" (Sokolova, 2008).

Russia's 76 plane strategic bomber force consists of "13 Tu-160s (Blackjacks), 32 Tu-95MS6s (Bear H6s), and 31 Tu-95MS16s (Bear H16s). Russia continues to modernize the targeting and navigation systems in many of these strategic aircraft." Russia's "advanced nuclear cruise missile (Kh-102) has been in development for more than 10 years but is still not deployed" (Norris and Kristensen, 2011 p. 71).

In addition to strategic forces, Russia maintains a significant number of tactical nuclear weapons. Estimates of their number vary considerably. The Congressional Commission on the Strategic Posture of the United States noted: "As part of its effort to compensate for weaknesses in its conventional forces, Russia's military leaders are putting more emphasis on non-strategic nuclear forces (NSNF), particularly weapons intended for tactical use on the battlefield. Russia no longer sees itself as capable of defending its vast territory and nearby interests with conventional forces…The combination of new warhead designs, the estimated production capability for new nuclear warheads, and precision delivery systems…open up new possibilities for Russian efforts to threaten to use nuclear weapons to influence regional conflicts" (Congressional Commission, 2009).

The United Kingdom

The United Kingdom has maintained operational nuclear weapons since 1956, but it gradually cut back its arsenal after the breakup of the Soviet Union. Currently the United Kingdom deploys nuclear weapons aboard Vanguard-class submarines that are projected to be operational until 2023. The stated purpose of British nuclear weapons continues to be to serve as a "minimum nuclear deterrent" (UK MOD, 1998, p. 323); the 2006 White Paper on the Future of the UK Nuclear Deterrent, reaffirmed the British policy of maintaining one submarine at sea continuously (United Kingdom Ministry of Defence, 2010). In May 2010, the U.K. Foreign Secretary stated that the U.K. government maintains a total of 225 nuclear weapons and will in the future maintain no more than that number (Hague, 2010).

The U.K. nuclear weapons effort is centered at Atomic Weapons Establishment (AWE) Aldermaston and AWE Burghfield, where most of the nuclear explosive package of the warhead for the submarine-launched ballistic missiles is designed and manufactured. AWE works closely with the U.S. nuclear weapon laboratories, and the Trident missiles for its submarines are leased from the United States. The NPT forbids transfer of nuclear warheads from the United States to the United Kingdom and vice versa. The United Kingdom has no nuclear-explosion test site.

France

France continues to maintain what it regards as a minimum deterrent force under its principle of "strict sufficiency"[2] while simultaneously modernizing and shrinking its nuclear arsenal (French Government, 2008). As of 2008, the French nuclear force consisted of fewer than 300 nuclear warheads.[3] The key component of the French deterrent force consists of four

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[2] "France applies a principle of strict sufficiency: she maintains her arsenal at the lowest possible level compatible with the strategic context" (Sarkozy, 2008).

[3] "After this reduction, I can tell you that our arsenal will include fewer than 300 nuclear warheads" (Sarkozy, 2008).

Le Triomphant-class SSBNs. The fourth boat in the class (Le Terrible) was deployed at the end of 2010. Each SSBN can carry 16 missiles armed with 4–6 warheads each.

The French nuclear air force consists of land- and sea- (carrier-) based aircraft configured to launch nuclear cruise missiles (Norris and Kristensen, 2008). The purpose of the aircraft is to provide an alternative mode of strategic nuclear attack to render the overall deterrent more credible. Under the present government, nuclear equipped aircraft stationed in France will be reduced to two squadrons, and one squadron will continue to deploy onboard the aircraft carrier Charles De Gaulle. The French government's 2008 Defense White Paper states of the new air-launched cruise missile:

> *"It will be equipped on deployment with the new… warhead. [New warheads] will replace the current warheads as they reach their maximum projected life expectancy, since manufacture of identical replacements cannot be guaranteed without nuclear testing. Because it will not be possible to prove performance by testing, the new missiles will be designed according to a 'robust warhead' concept validated during the final series of nuclear tests in 1995."* (p. 162)

France conducted a series of nuclear explosions at its Pacific test site in 1995, prior to signing the CTBT in 1996 and ratifying jointly with the United Kingdom on April 6, 1998. France has since closed and dismantled its test site. France maintains a stockpile stewardship-like program using high-speed computers; a linear electron beam accelerator used to take flash radiographic images of weapons components and is building a National Ignition Facility (NIF)-like facility for "simulation" of thermonuclear explosions (French Government, 2008 p. 54). A recent joint announcement by the U.K. and France establishes a collaborative effort to maintain their separate nuclear forces, including joint pulsed radiographic capability to be built by the U.K. at Valduc, France (Ingram, 2010).

China

China, like the other recognized Nuclear Weapon States under the NPT, has observed a moratorium on nuclear-explosion testing since 1996, when China last tested at the Lop Nor nuclear-explosion test facility. In 1996, China was the second country to sign the CTBT after the United States, but the National People's Congress of the PRC has yet to ratify the Treaty.

According to the U.S. Department of Defense, "Since 2000, China has shifted from a largely vulnerable, strategic deterrent based on liquid-fueled, intercontinental-range ballistic missiles (ICBMs) fired from fixed locations to a more survivable and flexible strategic nuclear force" (OSD, 2009, p. vii). The key change to the nuclear force involves the introduction of mobile solid-fueled Dong Feng (DF)-31 and DF-31A ICBMs to augment the liquid-fueled silo-based DF-5A and the introduction of new JIN-class SSBNs in an attempt to create a more survivable Chinese strategic deterrent.

According to the most recent DOD annual reports to Congress on Chinese military developments the Chinese maintain 50–75 ICBMs (OSD, 2010, p. 66 and OSD, 2011, p. 78). This estimate includes the DF-5A, DF-31 and DF31A, as well as the more limited range DF-4. The remaining delivery systems serve a medium- and intermediate-range role and are primarily positioned to hold regional targets at risk. According to official U.S. estimates, all Chinese nuclear-capable missiles carry a single warhead, but "China is also currently working on a range of technologies…including maneuvering re-entry vehicles, MIRVs, decoys, chaff, jamming, thermal shielding, and anti-satellite (ASAT) weapons" (OSD, 2010, p. 34; 2011, p. 34). China announced on January 11, 2010, a successful intercept of a mid-range ballistic missile, which further demonstrates China's capability to destroy satellites in low-earth orbit.

Today "the operational status of China's single XIA-class ballistic missile submarine (SSBN) and medium-range JL-1 submarine-launched ballistic missiles (SLBM) remain questionable" (OSD 2011, p. 34). In 2009, the U.S. DOD expected as many as five new JIN-class SSBNs to be deployed in the next few years (OSD, 2009, p. 48). Today the first JIN-class SSBN "appears ready, but the associated JL-2 SLBM has faced a number of problems and will likely continue flight tests. The date when the JIN-class SSBN/JL-2 SLBM combination will be fully operational is uncertain" (OSD, 2011, p. 34). Like its parent missile the DF-31, the Julang (JL)-2 has a reported maximum range of 4,500 miles (7,200 km) and would give "the PLA Navy its first credible second-strike nuclear capability" (ONI, 2009, p. 23). To hold targets at risk in the continental United States, the PLA Navy would need to extend submarine patrols beyond Chinese territorial waters; this would be an unprecedented posture change for China. "The PLA has only a limited capability to communicate with submarines at sea, and the PLA Navy has no experience in managing a SSBN fleet that performs strategic patrols with live nuclear warheads mated to missiles" (OSD 2011, p. 34).

China conducted all of its nuclear-explosion tests near Lop Nor in the sparsely populated northwestern part of the country. China stopped such testing in 1996 just prior to signing the CTBT, though it continues activities at its nuclear-explosion test site. As in the case of Russia at Novaya Zemlya, the possibility of very low-yield (hydronuclear) tests cannot be precluded without access to the test site. According to the Department of Defense and Energy, "China has had a fully functional and operating nuclear weapons infrastructure for over thirty years and is the only major nuclear power that is expanding the size of its nuclear arsenal. It is qualitatively and quantitatively modernizing its nuclear forces, developing and deploying new classes of missiles, upgrading older missile systems, and developing methods to counter ballistic missile defenses" (U.S. DOD and DOE, 2008, p. 6ff).

Finding 4-1: The Nuclear Weapon States have been able to maintain their nuclear weapons programs under a nuclear-explosion-test moratorium and are likely to be able to make nuclear weapons modifications that fall within the design range of their test experience without resorting to nuclear-explosion testing.

TEST-BAN COMPLIANCE ISSUES

In the CTBT text, the objectives of the verification regime are expressed in legal rather than technical terms. The absence of a technical definition is troubling for some. As discussed in Chapter 2, the technologies and locations for the International Monitoring System (IMS) are established by the Treaty. The legal definition of a nuclear explosion, which in turn determines what activities would constitute a Treaty violation, is a matter of negotiation history and mutual understanding, and it allows for case-by-case consideration of certain activities that are not prohibited. (See Box 4-1 below.)

The Department of State's article-by-article analysis of the CTBT outlines the understanding reached on activities not affected by the Treaty. According to this analysis, "Article I prohibits only explosions, not all activities involving a release of nuclear energy" (U.S. Department of State and Medalia, 2010, p. 17). The analysis describes types of activities that do not fall under the CTBT's prohibition.

BOX 4-1 Activities Not Prohibited Under the CTBT

The publicly available article-by-article Analysis by the U.S. Department of State indicates that specific examples of types of nuclear activities will NOT be prohibited under the CTBT. These activities include:

1. computer modeling
2. experiments using fast burst or pulse reactors
3. experiments using pulse power facilities
4. inertial confinement fusion (ICF) and similar experiments
5. property research of materials, including high explosives and fissile materials
6. hydrodynamic experiments, including subcritical experiments involving fissile material
7. operation of nuclear power and research reactors and activities related to the operation of accelerators.

By not defining precisely what is meant by a nuclear explosion, but by providing examples of what does not constitute a prohibition under the Treaty, it has been argued that there is substantial room for interpretation. In late 2011, the U.S. Department of State released a fact sheet that lists P-5 public statements on the scope of the CTBT negotiations and concludes that, “by the end of negotiations, all parties understood that the CTBT should be a true ‘zero yield’ treaty; nuclear weapon test explosions that produce any level of nuclear yield are prohibited” (U.S. Department of State, 2011b). The issue was addressed in the *2002 Report* (NRC, 2002, pp. 14-15), which did not attempt a technical definition of nuclear explosion. Neither do we attempt a technical definition in this report. It is not necessary to define a nuclear explosion to analyze the detectability and utility of nuclear explosion tests at various yields.

As described above, the NWS have all proved able to maintain their nuclear weapons programs under a test moratorium. However, any Party to the CTBT must consider that any other party might cheat on its commitment to the CTBT if it were deemed important and could be concealed with confidence. For example, Russia—and, to a lesser extent, China—both have experience with nuclear-explosion tests. They also have the knowledge and capabilities of the methods and difficulties of concealing such tests. Conversely, Russia and China also have a sophisticated science base for understanding nuclear weapons and are likely to be able to make nuclear weapons modifications (at least those that fall within the design-range of their test experience) without resorting to testing. In addition, the Russian and Chinese nuclear test sites are well monitored to very low limits, as described in Chapter 2 and Appendix D. It is possible that tests could be carried out at alternative sites with somewhat less capable detection limits. However, to advance new weapons designs, an extensive suite of test diagnostics must be employed, as well as multiple tests, making concealment of such activities difficult.

Hydronuclear Testing

Hydronuclear tests have merited a special place in the CTBT debate. This is in part because such tests are essentially impossible to detect by any known remote techniques. For example, a hydronuclear test fully contained in a properly designed explosive containment vessel would likely reveal nothing to remote monitors. Even intrusive, persistent local monitoring might find it difficult to detect such tests and to distinguish them from subcritical tests.

The United States historically used a definition of "hydronuclear" as being less than 0.002 tons (2 kgs) of yield.[4] However, another definition for a hydronuclear test involves a nuclear yield no larger than the energy provided by the chemical explosive that drove the implosion. Russia has historically defined "hydronuclear" tests as tests with a nuclear yield up to 0.1 ton (100 kg) of high-explosive equivalent.[5]

A related issue is the relevance or usefulness of such tests. These questions are considered here, under the assessment that hydronuclear tests, or very low-yield testing in general, are potentially of value primarily to experienced Nuclear Weapon States. In particular, there are real differences between U.S. and Soviet Union/Russian test histories with regard to the importance of hydronuclear testing. Some believe that these differences lead to differences in understanding of the testing limitations under the CTBT, either during the current moratorium on testing or possibly even after entry-into-force (EIF) of the CTBT, although, as noted above, the U.S. Department of State cites Russian statements and concludes that the scope of the treaty is not in question. China maintains that it does not conduct hydronuclear tests.[6]

U.S. Hydronuclear Test Experience

Thirty-five hydronuclear tests were conducted at LANL, and eleven were conducted by LLNL at NTS during the testing moratorium of 1958–61.They were carried out to resolve one-point safety problems in weapon systems already in production. The problems were not recognized until after the moratorium had started, so further nuclear-explosion testing was not an option (Thorn and Westervelt, 1987).

The U.S. hydronuclear tests consisted of reduced quantities of fissile material in generally full-up high explosive configurations. The maximum fission energy release was limited to no more than $0.5\text{x}10^{-6}$ kt (1 pound). On this basis, President Eisenhower designated such experiments during the moratorium as not being nuclear weapon tests. The one-point safety tests used the "creep up" method of adding fissile material and predicting the response of the weapon system from the experimental data. The largest fission release was less than 0.5×10^{-8} kt (0.01 pound).

During the moratorium, some consideration was given to the usefulness of hydronuclear experiments for nuclear weapons development, but the moratorium ended in 1961, and this approach was never pursued. This was more or less the situation until the renewed interest in the CTBT during the Clinton administration. A JASON study concluded that hydronuclear (or supercritical testing in general) was not required to maintain the existing U.S. stockpile, as long as a robust science-based stockpile stewardship program was established and maintained (JASON, 1994).

After more than a decade of experience with the SSP, leadership at the national laboratories advised the committee that hydronuclear experiments were not among the highest priorities for maintaining the existing U.S. stockpile. Even acknowledging that some people knowledgeable of nuclear weapons believe that hydronuclear tests would be valuable because they would exercise the various elements of nuclear testing, the laboratory directors, if they were given the flexibility to do hydronuclear experiments, would rather use the same resources to invest in SSP modeling and experiments (LLNL, October 2009, personal communication). Although hydronuclear experiments would have some technical value (e.g., repeated, identical

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[4] That is, the fissioning of 0.12 milligrams of uranium or plutonium, compared with the complete fission of 1.2 kilograms of the plutonium in the Nagasaki bomb.

[5] "Minatom defines a hydronuclear test as one with a yield less than 100 kg of high explosive equivalent" (NRC, 2002, pg. 67, ff 4.).

[6] Personal communication from a Chinese Academy of Engineering Physics (CAEP) official to two members of this committee.

hydronuclear tests might reveal symptoms of aging of nuclear pits), the committee finds that advanced pulsed radiographic facilities such as DARHT and even marginally subcritical tests at NTS could provide this information in the subcritical range explicitly allowed by all formulations of a nuclear-explosion test under the CTBT.[7]

Finding 4-2: Hydronuclear tests would be of limited value in maintaining the United States nuclear weapon stockpile in comparison with the advanced tools of the Stockpile Stewardship Program.

Soviet Union/Russian Hydronuclear Test Experience

Statements by Russian experts indicate that about 90 "hydronuclear experiments" were conducted by the Soviet Union and Russia up to 1990 (Mikhailov, 1996; 1998). It is unclear whether any such experiments have continued at the Novaya Zemlya test site since that time. Public statements indicate that perhaps an average of six "non-explosive" nuclear weapon-related experiments are conducted there annually, and it is clear that considerable resources have been devoted to maintaining the northern test site (RIA Novosti, 2006). It is conceivable that at least some of these experiments might have resulted in very low nuclear yields (< 1 ton), which could be completely contained in an explosive test vessel underground.

The histories of the Soviet Union's test programs note the usefulness of very-low-yield (hydronuclear) tests for weapon safety, as well as for data related to equations-of-state and as sources of radiation effects. Former Russian Minister of Atomic Energy, Viktor Mikhailov, classified experiments with nuclear energy release < 1 ton as "laboratory experiments…not nuclear weapon tests," and did not include them in the catalog of Soviet Union nuclear-explosion tests (Mikhailov, 1996).

Mikhailov catalogued 85 hydronuclear experiments at the Semipalatinsk test site from 1958 to 1989. These experiments were carried out unconfined on the surface and in tunnels at the Degelen Mountain site. Quoting the Mikhailov hydronuclear catalogue:

"A hydronuclear experiment is a physical experiment with a mock-up of a nuclear device with no considerable energy release (its value did not exceed that characteristic for a high explosive)" (Mikhailov, 1998).[8]

Early in the Soviet test history, a cadre of eminent Soviet physicists developed so-called "non-explosive chain reaction" (NCR) experiments. These apparently were high-energy-density weapon physics experiments that yielded valuable data, for example, related to the equations of state of plutonium and uranium under extremes of pressure and temperature.[9] Such testing appears to have been a much more integrated part of the nuclear weapons development program in the Soviet Union than it was in the United States. Thus, it seems at least plausible

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[7] Finally, if in the unlikely event that a problem with the stockpile, other than one-point safety, required a return to nuclear-explosion testing, greater yields would be necessary than those associated with hydronuclear tests.

[8] This formulation is consistent with a hydronuclear yield limit of 0.1 ton (100 kgs.)

[9] According to Styashkin (2002) and Altshuler et al. (1997), "Approximately 40 non-explosive chain reaction (NCR) experiments were conducted in 1958, 1960, 1961, and 1963 for the purpose of creating plutonium and uranium state equations." Also, "A value of nuclear energy release equivalent to 1 kg of TNT…[was] accepted as the upper boundary of the NTsR [NCR] range."

The "non-explosive chain reactions" (NCR, also called "unexploded chain reactions" or UCR) thus played an important role in the development of Soviet nuclear weapons, in contrast to the U.S. program for which these hydronuclear reactions with a yield well below 2 kg of TNT were used only for evaluation of nuclear warhead safety.

that repeated NCR experiments could be helpful in maintaining the existing inventory of Russian nuclear weapons, perhaps including life extension and modifying materials to improve safety.

Although a carefully conducted ("contained") hydronuclear series would in principle go undetected, even by an advanced USAEDS, it might still be revealed by other intelligence methods. For a nascent nuclear-weapons program, such a series would be costly in terms of plutonium or highly-enriched uranium. Still, a state might choose to conduct such tests, which could not be detected by the United States or by the IMS. At the same time, however, we have been unable to identify any significant advantage that could accrue to a State testing at these very low levels (<1 ton).[10] See Box 4-2 for further discussion on this point.

Finding 4-3: Based on Russia's extensive history of hydronuclear testing, such tests could be of some benefit to Russia in maintaining or modernizing its nuclear stockpile. However, it is unlikely that hydronuclear tests would enable Russia to develop new strategic capabilities outside of its nuclear-explosion test experience.

BOX 4-2 Extended Deterrence Implications for Nuclear Testing

The U.S focus for the last 60 years has been on strategic nuclear deterrence of the Soviet Union, and now of Russia. However, the Russian focus, certainly in the last decade, has been on its neighbors and NATO. In addition to its strategic forces, Russia maintains a substantial arsenal of tactical nuclear weapons. Some believe that Russia is planning to develop new or adapted low-yield tactical weapons suitable for use on its own soil as compensation for its conventional military's perceived inability to resist invasion. Russia could almost certainly field new low-yield tactical weapons based on past designs, without new nuclear-explosion tests. Thus, those capabilities could be developed undetected with or without the CTBT. Although tactical nuclear weapons may not threaten United States' territory directly, they could threaten U.S. allies, especially those bordering the Russian Federation. The United States must consider such a possibility in its defense planning.

We have not been able to identify any aspect of this potential threat that would require the United States to resume nuclear-explosion testing in order to respond. If it were determined in the future that the United States needed to adapt its existing nuclear arsenal to field comparable capabilities, it is highly likely that the existing U.S. test experience would enable the necessary actions without further nuclear-explosion testing.

China Hydronuclear Test Experience

Given China's apparent lack of hydronuclear test experience, it is not clear how China might utilize such testing in its strategic modernization.

PROBABILITY OF DETECTION VS. PROBABILITY OF EVASION

The probability of detecting underground nuclear explosion tests is a primary focus in assessing monitoring capabilities, as described in Chapter 2. Assessing the detection probability allows the United States to determine what level of risk could be posed by undetected activities. However, from the perspective of a potential evasive tester (e.g., one intent on testing below the detection limit), the question of interest will be different. Specifically, an evasive tester will wish

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[10] The *2002 Report* noted that the one benefit a State might gain from such very low yield tests would be to improve one-point safety. Such a step would not, standing alone, impair U.S. security.

to assess the probability that a nuclear-explosion test will go undetected. We will call this the *probability of evasion* (i.e., the probability of successfully avoiding detection by the seismic monitoring systems). If the consequences of detection are severe, such as being caught violating a major international obligation, the evasive tester will presumably want to ensure that the probability of detection is low and hence will want to test well below the 90 percent detection limit.

To evaluate the evader's risk, we use the example of seismic monitoring and the same statistical approach that was used in assessing the probability of detection, where we quote the device yield[11] that would be detectable 90 percent of the time. For instance, for the specific case of using the IMS network threshold of m_b = 3.4 in Asia, Europe and North Africa, the probabilities of detecting an explosion in hard rock are given in Table 4-1 below (see also Chapter 2, Table 2-1, and Box 2-1 on magnitude-yield relations). The detection probability in regions of better propagation is expressed as 90 percent confidence at 90 tons (0.09 kilotons). This means that if ten 90-ton explosions took place, we would expect to detect nine (90 percent) of them. From the evader's perspective, this level of detectability means that out of 10 attempted nuclear explosions, only 1 would go undetected on the average by seismic monitoring, (i.e., the probability of successful evasion is only 10 percent at 90 tons). Conversely, if the evader wishes to have a 90 percent probability of successful evasion, the level of the test allowed would have to be much lower. For example, the global IMS seismic detection threshold at the 10 percent level is shown in Figure 4-1 and for Asia, Europe and North Africa gives a threshold of detection of about magnitude 3.0. These IMS Asia, Europe and North Africa magnitude thresholds are converted into explosion yields in Table 4-1, in which yield limits are given for 90 percent probability of evasion (10 percent probability of detection). The comparison shows that in order to increase the probability of evasion from 10 percent to 90 percent, the yield of the nuclear-explosion test must be reduced by about a factor of three.

TABLE 4-1: Detection vs. Evasion Probabilities for Fully Coupled Underground Nuclear Explosion Tests: Average for Asia, Europe and N. Africa--Illustration Based on Capabilities Using Only IMS Primary Stations in 2007.

Yield (kilotons) Hard Rock, Regions of Better Propagation[12]	Yield (kilotons) Hard Rock, Regions of Poorer Propagation[13]	Probability of Seismic Detection (fully coupled)	Probability of Evading Seismic Detection (fully coupled)
0.09	0.22	90 percent	10 percent
0.035	0.09	10 percent	90 percent

SOURCE: Committee

Evasion maps can be made in exactly the same way as the probability of detection maps of Chapter 2. It is possible to look at 90 percent successful evasion thresholds by looking at 10 percent probability of detection maps. An example of this map for the IMS stations is shown in Figure 4-1. (It is analogous to Figure 2-8 except the probability of *detection* has been changed from 90 percent to 10 percent; i.e., a probability of 90 percent of avoiding seismic detection.)

Finding 4-4: An evader determined to avoid detection would test at levels the evader believes would have a low probability of detection.

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[11] The non evasively tested or fully coupled "device" refers to the nuclear explosive under test

[12] m_b = 4.45 + 1.0 log (yield in kt)

[13] m_b = 4.05 + 1.0 log (yield in kt)

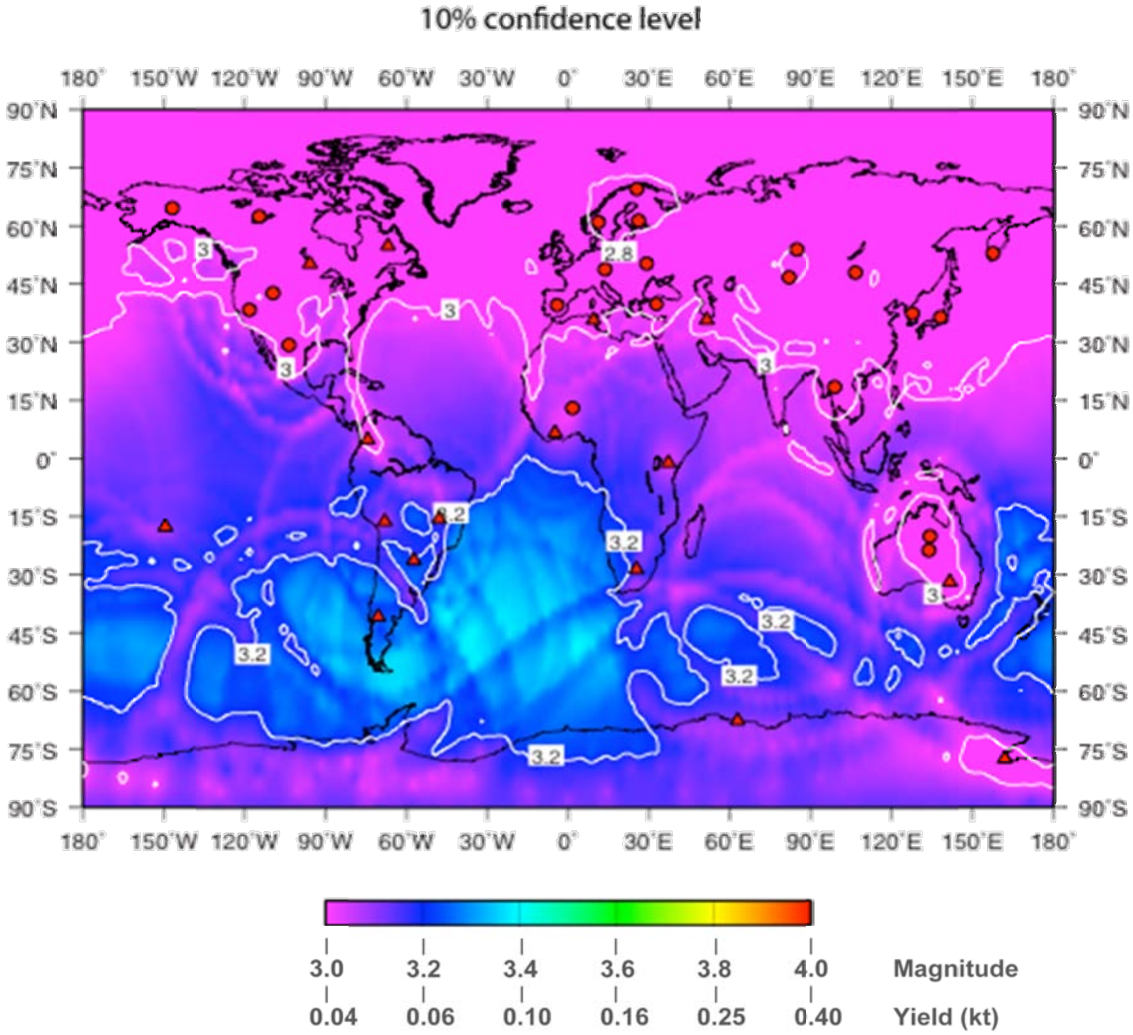

FIGURE 4-1: Map of 10 percent confidence detection levels (90 percent probability of avoiding detection) for the primary IMS Network (2007). The map represents detection capability of IMS primary seismic network, late 2007, with 38 stations sending data to the IDC. Contours indicate the magnitude of the smallest seismic event that would be detected with a 10 percent probability at three or more stations. Red circles are seismic arrays, and triangles are single seismic stations. This map is similar to Figure 2-8, except the probability of detection is 10 percent here rather than 90 percent in Figure 2-8. For reference, the magnitudes 2.8, 3.0, and 3.2 correspond to fully coupled device yields of 0.022 kt, 0.035 kt, and 0.056 kt respectively in regions of better propagation (The magnitude yield relationship comes from Box 2-1 in Chapter 2).
SOURCE: Capability map prepared by Tormod Kværna and Frode Ringdal, NORSAR

The probability of repeatedly achieving a certain goal, such as successfully evading detection, goes down rapidly with the number of attempts. For instance if an evasive tester has 90 percent confidence of evading detection on one test, there will be only 81 percent confidence for evading detection on 2 tests and only 73 percent confidence of evading detection on 3 tests, etc. Historically, Nuclear Weapon States have conducted multiple nuclear-explosion tests to develop sufficient confidence in the performance of a given weapon type. The committee notes, however, that nations could develop rudimentary fission weapons without testing, or more advanced weapons if provided with a previously tested design.

However, even in a world in which nuclear-explosion testing is constrained (e.g., potentially through the CTBT), it is possible that a State—whether currently acknowledged to possess nuclear weapons or not—may derive value by the conduct of just one nuclear-explosion test. For example, a nuclear weapons State may be able to address and/or confirm the resolution of an important technical problem with a warhead. Alternatively, an aspiring nuclear State might, as the United States did with the Trinity test, choose to confirm the performance of an implosion-type warhead. In these cases, a State might be willing to accept the risk level presented by one test only.[14]

Evasive Underground Testing

The *2002 Report* addressed clandestine scenarios for evasive nuclear-explosion testing and concluded that only two warrant serious discussion: cavity decoupling--reducing the size of the seismic signal created by an explosion by muffling the explosion in a large underground cavity, and mine masking--concealing a nuclear explosion by conducting a nuclear-explosion test in a region that has frequent, large chemical explosions associated with mining operations.[15] The 2010 committee again concludes that these are the only evasion scenarios that warrant serious technical exploration at the present time. The understanding of decoupling is supported by a very small test base, which is mainly derived from chemical explosions and has not changed appreciably in the past 10 years. As a result, there remain significant uncertainties in predicting the level of decoupling, especially for yields of a kiloton or more and in geological media other than salt. Thus for a clandestine tester to have strong confidence that a test would not be detected, it would be prudent to limit the planned test yield to levels concealable to the lower range expected for decoupling factors. The utility of mine masking is similarly limited, in this case by the well-known temporal signatures of mine blasts, their relatively small size, and the extensive base of seismic knowledge for mining regions. A more detailed technical discussion of evasive testing is presented in Appendix E.

Cavity Decoupling

Cavity decoupling is achieved by conducting the nuclear-explosion test inside a large chamber, such that ground motions are less efficiently generated than if the nuclear device were in close contact with the surrounding rock (the case of a well coupled or fully coupled explosion is used as the comparison point to assign the effectiveness of the technique). When decoupling is successfully accomplished, the explosion is muffled. Decoupling reduces the strength of seismic waves generated by an underground explosion and is characterized by a “decoupling factor” or DF.[16]

The volume of the cavity needed to achieve full decoupling increases linearly with the explosive yield. To achieve the maximum value of DF possible for a given yield, the pre-existing cavity must be sufficiently large that the surrounding rock does not fracture or deform

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[14] It is also possible, as was the case for the DPRK, that a State might wish to demonstrate (for political purposes) that it possesses nuclear weapons, in which case the risk assessment does not apply.

[15] “The experimentation needed to explore other approaches to evasion would be highly uncertain of success, costly, and likely in itself to be detected. Thus the only evasion scenarios that need to be taken seriously at this time are cavity decoupling and mine masking” (NRC, 2002, p. 6).

[16] DF is the ratio of the actual device yield divided by the apparent yield measured remotely by seismology, DF=1 for a fully-coupled explosion.

permanently (i.e., it is not stressed beyond the elastic limit). Such a “fully decoupled” explosion produces seismic waves in the Earth’s crust, but most of the energy goes into increasing the gas pressure in the cavity, thereby reducing the apparent yield of the original explosion by the factor DF. Once this limit is reached, increasing the volume of a cavity does not further increase the decoupling factor.

Larger explosions (>1 kt) are far more challenging to decouple than are smaller explosions because of the compounding of several difficulties. First, a larger cavity is required, which is more challenging to construct than a smaller cavity (e.g., Leith, 2001). It is noteworthy that the only nuclear-explosion tests known to have been decoupled (a Soviet Azgir test in 1976 and the U.S. Sterling test in 1966) used cavities that had previously been created by much larger well coupled nuclear explosions (see Figure E-1 in Appendix E).[17] Second, a greater depth is needed, both to accommodate the larger cavity, and to contain the high gas pressure generated by the explosion.[18] Third, the larger and deeper a cavity is, the harder it is to avoid cavity collapse before the nuclear explosion can be detonated.

Large *non-spherical* cavities in hard rock of the same volume are easier to construct and have been proposed for clandestine testing (Stevens et al., 1991; Leith, 2001; Murphy, 2009). The surface area of non-spherical cavities, however, is greater than that of a sphere of the same volume. Hence, the chance that more faults, cracks and joints would be encountered at the surface of a non-spherical cavity increases the chance that radionuclides could escape and be detected. The shortest dimension of non-spherical openings in hard rock will experience a more intense non-elastic pressure pulse compared with that experienced on the wall of a fully decoupled nuclear explosion of the same size in a spherical cavity.

Because of the challenge of creating sufficiently large cavities, nuclear scientists have long recognized the benefit to conducting experiments in geological salt deposits. There, large cavities can be formed by solution mining[19] or cavities from previous nuclear-explosion tests in salt also may be used. In fact, the largest decoupling experiments, Azgir and Sterling, were both conducted in salt, so the most reliable information is available for this medium. Salt is relatively weak so it is difficult to create a large, air-filled cavity, especially at greater depth (Leith, 2001). In contrast, hard rock is strong enough to support large cavities but at much greater effort in excavation through conventional mining techniques (i.e., if one does not use a naturally occurring cavity or one created by a previous well coupled nuclear explosion).

The maximum decoupling factor value documented to date is DF = 70(+/-8)—for the 380 ton (0.38 kt) Sterling test in a cavity created in a geological salt deposit by a previous much larger nuclear explosion (5.3 kt yield). This means that the waves measured were equivalent to those that would have been produced by a 380/70 = 5.4 ton well-coupled explosion. However, because of the limited nuclear-explosion test history for decoupling, predicting the effectiveness of a decoupling attempt is uncertain. For instance, if a decoupled test were to be attempted in a hard rock area, the available information[20] indicates that the decoupling factor would be smaller than that for salt, about 20-40 rather than 70. Observations to date also indicate that explosions with yield above 1 kiloton (e.g., the Soviet test at Azgir) exhibit less decoupling—with DF 10-

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[17] The Mill Yard test is not included here because it was not contained and the amount of decoupling is uncertain (OTA, 1989 p. 4; Sykes, 1996; Murphy, 2009). It is briefly summarized in Appendix E.

[18] The ‘Latter criterion’ for containment requires that the pressure due to the weight of the overlying rock be at least twice the pressure generated in the cavity by the explosion. Thus a larger explosion requires a larger cavity, greater depth, or both as summarized in Figure E-4. The pressure under a thickness h of rock having density ρ is ρgh, where $g = 9.8$ m/s^2 is the acceleration of gravity (ρ is typically between 1.5 and 3 g/cm^3). The Latter criterion is intended to ensure that the rock surrounding a cavity remains in compression during and soon after an explosion, thereby preventing venting of gases.

[19] Dissolution of salt by flushing large amounts of water through the growing cavity.

[20] The only tests in hard rock involved chemical explosions ranging in yield from a few pounds to about 10 tons.

20—than the sub-kiloton Sterling and chemical explosion tests. It is not well understood why decoupling is less effective at multi-kiloton yields and in hard rock than for sub-kiloton yields and in salt. Part of the problem when comparing chemical with nuclear explosions is the large difference in the source energy density.

The very limited nuclear test data on decoupling are shown in Figure E-1 in Appendix E. Calculations of decoupling have significantly overestimated the decoupling factor (by factors of 1.8-4) compared to observations. It may be that the heterogeneity of the Earth's crust (including the presence of fractures) and the effects of non-elastic deformation are the cause of these too-high theoretical predictions of decoupling. Additional research taking advantage of advanced computation could help develop a better understanding of these phenomena as an aid to developing more effective monitoring measures. Such computation must be based upon adequate understanding of the material properties of rock on length scales much greater than can easily be measured in the laboratory.

For a potential evader, the uncertainty in the actual amount of decoupling would present a difficult technical challenge.

Mine Masking

Masking is intended to hide the occurrence of a nuclear explosion by conducting the test in a region that has frequent, large chemical explosions associated with mining operations: the motivation is that although the nuclear-explosion test might well be recorded, it would be incorrectly identified as just another conventional explosion associated with the mining operations in the region.

Mining operations detonate large explosions in a "ripple-fired" sequence, not as a single explosion, because fracture and excavation of rock are much more successful with a rapid sequence of blasts than with a single detonation and local seismic damage to infrastructure is minimized. Seismic methods can distinguish between a single, large explosion and its ripple-fired equivalent. Therefore, any single large explosion would be considered suspicious, whether or not it occurred in a mining area. As a confidence building measure, the CTBT provides for voluntary reporting of conventional explosions exceeding 300 tons yield (e.g., for mining, scientific research or other purposes). Some nations, including the United States, now voluntarily publish lists of known mine blasts that generate seismic signals.[21]

Past research (Smith, 1993) has shown that to mask a nuclear explosion, the event would have to have a yield less than 10 percent that of the masking explosions. It is therefore impractical to mask nuclear-explosion tests having device yields above 10-50 tons (see Appendix E). Moreover, mining regions with large numbers of explosions tend to be well characterized by seismology, because the blasts act as seismic sources that are picked up by regional stations, further limiting the utility of mine masking as a means of evasion. Additional information about mine masking is in Appendix E.

Finding 4-5: Mine masking is a less credible evasion scenario than it was at the time of the *2002 Report* because of improvements in monitoring capabilities.

Monitoring Evasive Nuclear-Explosion Tests

The decoupling factors given above are for frequencies below 1–2 Hz. The seismic signal from a decoupled signal is less effectively reduced at the higher frequencies characteristic of regional monitoring (~10-40 Hz), as shown in Figure E-3 of Appendix E. These

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[21] See USGS web page: *http://earthquake.usgs.gov/earthquakes/eqarchives/mineblast*.

higher frequency signals are detectable at shorter distances (up to ~1,600 km [1,000 miles]) than are the lower frequency signals and thus can best be detected where there is a dense network of sensing stations, as is increasingly the case in Eurasia.

Unlike the understanding of decoupling itself, in the past 10 years, the capabilities of detection have advanced significantly. The IMS, when complete, (as summarized in Table 4-1) will provide a 90 percent global seismic detection limit of about 0.2 kt for a fully coupled nuclear-explosion test in hard rock. In addition, regional monitoring and focused monitoring at known or suspected test sites can detect explosions of much lower seismic yield, as for instance the 5-15 ton detection limit at Novaya Zemlya (see Appendix D) that is a result of U.S.–Norwegian cooperation in this area. As noted in the previous section, such limits are conventionally taken as a 90-percent probability of detection.

For 90-percent probability of avoidance of detection, the yield must be reduced by another factor of about 3. For Novaya Zemlya, the probability of successful evasion yield range would be about 2–5 tons. Using the range of decoupling factors that we consider plausible for hard rock (20-40), this corresponds to a device yield of at most 200 tons at this site to reduce the probability of detection to 10 percent. For comparison, applying the factor of 3 reduction for a high probability of successful evasion to the IMS global detection threshold leads to a fully decoupled device yield of about 90 tons (as shown in Table 2-2). In Appendix E, the Seismology Subcommittee describes several other regions of monitoring concern for which the possibility of decoupling leads to threshold capabilities similar to those described above for Novaya Zemlya. In general the Subcommittee argues that it is not credible for decoupled nuclear-explosion testing to be successfully hidden at yields above about 1 kt.

Table 4-2 summarizes the capability of the IMS seismic detection component and open regional systems to detect and locate underground explosions at two probability of detection levels, 10 percent and 90 percent, and in various regions of the world. Columns 3 and 4 show the potential impact of cavity decoupling for evasion with the anticipated DF = 70 for a cavity in salt and for an assumed DF of 20-40 for a cavity in hard rock. With continuing development of new capabilities, up to a 3-fold increase in sensitivity over the values shown in Table 4-2 may be achieved. The technical developments that could support this potential improvement include some combination of the use of array processing as implemented experimentally in the Smart Array experiment in Scandinavia (see Appendix D); waveform correlation methods; or other signal processing enhancements that might lead to further improvement in detection threshold, perhaps combined with the use of additional stations.

The entries in the table are marked (bold) for the 10-percent detection probability, which the Committee judges is the largest that would be used by a potential evader for planning purposes. Detection thresholds for regions of interest to the United States, such as Asia, including Russia and China are noted. The test sites in Russia, China, and North Korea can be monitored by IMS and USAEDS stations considerably more sensitively, and analysis of events around these test sites has been assisted by additional data from open seismic networks, further increasing sensitivity.

TABLE 4-2: Seismic Detection Thresholds of Coupled or Decoupled Underground Nuclear Explosions at 10-Percent (shown in bold face) and 90-Percent Detection Probability Based on Use of Both IMS and Open Monitoring Networks.

Monitoring Confidence Levels (2010 Networks) (1) (2)	**Detection Thresholds (2010 Networks) *Maximum Explosive Yield* (3)**		
	Fully Coupled (kilotons)	**Cavity Decoupled (kilotons)**	
		Salt, DF = 70 Bomb-produced or solution-mined cavity	Hard Rock DF = 20-40
1	**2**	**3**	**4**
Regional detection *low-probability* (~10%) detection threshold. *(seismic magnitude: 2.2)(4)*	**0.006**	**0.4**	**0.1–0.2**
Regional detection *high-probability* (~90%) detection threshold. *(seismic magnitude: 2.8) (4)*	0.02	1.6	0.4–0.9
Teleseismic detection *low-probability* (~10%) detection threshold for Asia, Europe, N. Africa and N. America. *(seismic magnitude: 3.0)(5)*	**0.04**	**2.5**	**0.7–1.4**
Teleseismic detection *high-probability* (~90%) detection threshold for Asia, Europe, N. Africa and N. America. *(seismic magnitude:3.4) (5)*	0.09	6.2	1.7–3.6
Teleseismic detection *low-probability* (~10%) detection threshold for other regions. *(seismic magnitude:3.4)(5)*	**0.09**	**6.2**	**1.8–3.6**
Teleseismic detection *high-probability* (~90%) detection threshold for other regions. *(seismic magnitude:3.8)(5)*	0.2	16	4–9

(1) Explosive yields are estimated from the relationship seismic magnitude m_b = 4.45 + 1.0 log Y (kt) for fully coupled sub-kiloton explosions in a tectonically stable area. In regions that are tectonically active, a comparable seismic magnitude could be associated with a yield about four times larger.
(2) *Regional* refers to event-station distances of less than about 1,600 km (1,000 mi), and *teleseismic* refers to event-station distances greater than about 1,600 km.
(3) There is potential for significant improvement in these thresholds. See text for details.
(4) Based on regional networks discussed in Chapter 2.
(5) Based on IMS network thresholds described in more detail in Chapter 2.

SOURCE: Committee

Table 4-2 indicates that, in principle, fully decoupled underground nuclear-explosion tests in salt cavities might be conducted (e.g., in remote areas of Russia) with yields up to nearly 3 kt with only a 10-percent probability of teleseismic detection by the IMS. The Table is useful for making comparisons (for example, to demonstrate the importance of regional monitoring vs. teleseismic), but it should not be interpreted to convey practical realities or bottom-line capabilities. Achieving a DF of 70 for an explosion as large as a kiloton is not supported by practical experience (see Appendix E), suitable salt domes in which cavities could be solution-mined exist in a very limited number of places in the world (most not on the current territory of Russia), and the committee believes that efforts to conduct solution mining of cavities on these sites would likely be detected by various intelligence methods.

Although the committee adopts a DF of 20-40, for hard rock, no cavity-decoupled nuclear explosion has been attempted in hard rock (see Appendix E). In addition, fully decoupled explosions in hard rock do not deform the rock plastically and hence are likely to leak radioactive materials from cracks and joints in the rock.

The data in Table 4-2 are the basis of the following finding.

Finding 4-6: With the inclusion of regional monitoring, improved understanding of backgrounds, and proper calibration of stations, an evasive tester in Asia, Europe, North Africa, or North America would need to restrict device yield to levels below 1 kiloton (even if the explosion were fully decoupled) to ensure no more than a 10-percent probability of detection for IMS and open monitoring networks.

There has been no experience with nuclear explosives tested in cavities in salt prepared by solution mining. Although it is possible for a country to clandestinely solution-mine a cavity in a salt dome, all cavities prepared by nuclear explosives are well located. A State could not mine a cavity in another State without that State's knowledge. With the breakup of the Soviet Union, Russia no longer contains the many salt domes of the Pre-Caspian Depression in Kazakhstan, and "bedded salt" is less suitable for containing a nuclear explosion than is a cavity in a salt dome—due to greater likelihood of leakage of radioactive materials. Given the lack of experience anywhere in the world with fully decoupled nuclear explosion testing in mined salt or hard rock, and the likelihood that an evasive tester would probably test at or below the 10 percent detection probability, we find that cavity decoupling as a means of escaping detection by the IMS is decreasingly credible at device yields above 1 kt. The exception is in explosively produced cavities in salt domes; such cavity production would be eminently detectable by the IMS, and existing cavities are for the most part unsuitable and in any case could be closely monitored.

Finding 4-7: For IMS and open monitoring networks, methods of evasion based on decoupling and mine masking are credible only for device yields below a few kilotons worldwide and at most a few hundred tons at well-monitored locations.

Finding 4-8: The States most capable of carrying out evasive nuclear-explosion testing successfully are Russia and China. Countries with less nuclear-explosion testing experience would face serious costs, practical difficulties in implementation, and uncertainties in how effectively a test could be concealed. In any case, such testing is unlikely to require the United States to return to nuclear-explosion testing.

Finding 4-9: Better technical understanding of the decoupling process in various types of geologies would likely improve the capability to detect evasive nuclear-explosion testing.

Recommendation 4-1: If the possibility of evasive nuclear-explosion testing through cavity decoupling continues to be a concern, the United States should:

- **Apply modern computational and experimental methods to understand the decoupling process in various geologies;**
- **Identify areas such as geologic salt domes advantageous for decoupling and consider the need for additional monitoring; and**

- **Identify indicators that a country is using—or may be planning to use—decoupling as an evasion strategy.**

TECHNICAL SIGNIFICANCE OF DIFFERENT LEVELS OF TESTING

The information presented in the previous sections concerning the nuclear programs of other States with advanced nuclear weapons (Russia and China), the definition of a *nuclear explosion* under the CTBT, and the risk of detection entailed in attempts to test evasively, now allow us to return to the key question of this chapter. This is the assessment of the potential threats to U.S. security that undetected testing might pose. In addressing this question, we will consider both the issues of improvements in weapons capabilities of an existing nuclear State, more succinctly termed *vertical proliferation*, and the spread of nuclear weapons capability to new States or actors, *horizontal proliferation.*

The committee concludes that the States most able to carry out successful evasive testing are Russia and China. (Note that France has decommissioned its test site, and the United Kingdom utilized the U.S. test site in Nevada.) Russia, based on its more extensive history of using very-low-yield testing as part of its nuclear weapons development program, could use low-yield evasive tests to help modernize its existing nuclear stockpile or even develop new types of lower-yield tactical weapons. How China might utilize low-yield evasive testing in its strategic modernization is unclear. Other States might also benefit from low-yield evasive testing but with higher risk of detection and higher risk that their nuclear weapons, if deployed, would not perform as intended.

The committee agrees with the *2002 Report* assessment that the Nuclear Weapon States recognized by the NPT would be more likely to succeed in evasive testing than States with less nuclear experience. However, the committee is not aware of any benefits from such testing that would require the United States to return to testing. Non-Nuclear Weapon States, or those with limited testing experience, might derive some limited benefit from low-yield or evasive testing—albeit with a higher risk of exposure. At the other extreme, a return to full-yield nuclear-explosion testing would likely present new strategic threats to the United States (see Box 4-3 below), not only from Russia and China, but also from proliferant States, either in violation of or outside of the NPT. Whether or not the United States would need to return to testing would depend on complex technical and political factors.

BOX 4-3 Examples of Nuclear Weapons Advanced Development:
Limitations Imposed by CTBT Constraints on Testing

There are examples of advanced nuclear weapons technology that the U.S. assessed during the period of nuclear testing. It is likely that the Soviet Union/Russia pursued similar development paths. The examples were not taken beyond technology development to weaponization in the U.S. primarily because there was never a validated military requirement. To weaponize these concepts would have required several multi-kiloton tests. This is still likely to be the case today. Such tests would likely be detectable under the International Monitoring System.

Constraints of a Test Ban

There is no expectation that cessation of nuclear-explosion testing, by itself, will automatically result in elimination of nuclear weapons or will prevent nuclear weapons proliferation. The achievements of the U.S. Stockpile Stewardship Program provide evidence that an existing nuclear weapons program can be maintained in the absence of testing, even though testing played a crucial role in the original development of nuclear weapons. Similarly the other NWS under the NPT since 1996 have committed publicly to maintain, and in a few cases to modernize, their nuclear weapons capability without testing. Thus for States that already have a nuclear weapons capability, foregoing testing limits vertical proliferation, constraining the development of new nuclear capabilities but not the ability to maintain a nuclear capability.

Similarly, the effect of the CTBT on horizontal proliferation will be to inhibit, but not eliminate, all potential dangers. However, the cost and effort and the risk of discovery to countries pursuing such horizontal proliferation clandestinely will be greatly increased.

Today the widespread availability of scientific knowledge and computing power make the technical barriers to horizontal proliferation, at least by a reasonably technically sophisticated nation, lower than at any time in the past, with or without testing. These technical barriers will continue to diminish as computing power becomes cheaper and as knowledge relevant to weapons spreads globally. The difficulty in obtaining the necessary fissile materials, under the NPT norm, is a barrier at least as great as limitations that would be imposed on testing by the CTBT. Finally, India, Pakistan, and perhaps now North Korea, have developed and are continuing to develop a militarily significant (at least in their region) nuclear weapons capability with only a few tests carried out with no attempt to conceal them from detection.

Finding 4-10: Threats could arise by clandestine nuclear weapons activity. For instance, a country with no testing experience and a modest industrial base could confidently build and deploy a single-stage, unboosted nuclear weapon without any testing, if it had access to sufficient quantities of fissile material. These advances could be made whether or not the CTBT were in force. However, it is highly likely that the United States could counter these threats without returning to nuclear-explosion testing and thus could respond equally well whether or not the CTBT were in force.

Although the broader value of limitations on testing to inhibit both vertical and horizontal proliferation must be considered within the context of diplomatic, military, and economic incentives/disincentives, these matters are beyond the scope of this report. In the following, we will present the technical assessment that is needed to inform policy decisions, which will certainly include consideration of these other factors.

Technical Constraints on Nuclear Weapons Development Posed by Testing with Intent to Avoid Detection by States with Varying Levels of Nuclear-Explosion Test Experience.

Table 4-3 summarizes technical constraints on nuclear weapons development posed by testing with intent to avoid detection by States with various levels of nuclear-explosion test experience: countries with greater prior text experience versus countries of lesser or no test experience. Note that it is assumed here that the States have made the commitment to the risks of clandestine testing and will test only to the level where they could have high confidence that they would escape detection; that is, no detectable indicators of a nuclear explosion. The evasion scenario explicitly considered here is cavity decoupling of underground explosions (see previous discussion on evasive nuclear-explosion testing).

Various levels of yields are shown in Table 4-3, starting with subcritical experiments (permitted under the CTBT), and increasing through levels of nuclear explosion yields up to 10 kt or greater. The table indicates plausible technical improvements at each level of testing that could accrue to countries with and without significant prior test experience.

Concealing a test at the 1 kt level (or higher) with high confidence of not being detected is judged to be unlikely even by an advanced nuclear weapons State such as China or Russia, especially where a series of such tests would be required for the high confidence development of a destabilizing new nuclear capability. On the other hand, testing below 0.001 kt is judged likely to remain undetected via objective physical or chemical evidence. Testing at levels between these extremes presents increasing risk of discovery with higher yield, and would depend upon the levels of effort and competence to evade detection—e.g., by cavity decoupling.

The significant advances in nuclear explosion detection capabilities discussed in Chapter 2, and the issues of detection (and evasion) probability discussed in this chapter are reflected in this table, which updates a similar table that appeared in the *2002 Report*. The committee's intent in including this assessment is to provide the reader with a general idea of how easy or difficult it is to detect underground testing at different levels relative to the plausible technical achievements for underground testing; this summary does not represent any particular sensor network, medium, or location. Now, as in 2002, the 2012 committee recognizes that any such table risks oversimplifying a complex technical set of issues.

Thus, for the countries with greater nuclear-explosion test experience, capabilities increase from pursuing modifications of previously tested designs using very low yields (< 1 ton), possibly with evasive testing to avoid detection, to virtually unconstrained development of new or modified weapons with yields greater than 1 kt, very likely to be detected even with attempts at evasion.

For the countries with lesser nuclear-explosion test experience or design sophistication, capabilities range from exploring nuclear weapon physics and gaining experience and confidence with weapons physics experiments at very low yields (< 1 ton), to pursuing more complex implosion weapon designs by testing at yields up to and beyond 1 kt.

Regarding members of the "lesser experience" group, the most significant conclusions related to testing are, first, that they rely heavily on indigenous technical sophistication (perhaps with outside assistance) and, second, that they appear to be the most likely of any group to decide that even a single multi-kiloton test (with or without attempts to conceal) would strengthen confidence in their nuclear weapon capability.

The conclusion from the analysis above is that constraints placed on testing by the detection capabilities of the IMS, and the better capabilities of the U.S. NTM, will reduce the likelihood of successful clandestine nuclear-explosion testing, and inhibit the development of new types of strategic nuclear weapons. But the development of weapons with lower capabilities, such as those that might pose a local or regional threat or be used in local battlefield scenarios, is possible with or without the CTBT under various conditions for countries of different levels of nuclear sophistication. Again, such developments would not require the United States to return to testing in order to respond.

TABLE 4-3: Purposes and Plausible Technical Achievements for Underground Testing at Various Yields in the Absence of Horizontal Proliferation.

Yield (tons of TNT equivalent)*	**Countries of lesser prior nuclear-explosion test experience and/or design sophistication** (advances achievable in the specified yield ranges also include all of those achievable at lower yields)**	**Countries of greater prior nuclear-explosion test experience and/or design sophistication (items in column to left, plus)**
Subcritical experiments (permissible under the CTBT)	• Equation-of-state studies • High-explosive lens tests for implosion weapons • Development and certification of simple, bulky, relatively inefficient unboosted fission weapons (e.g., gun-type weapon)	• Limited insights relevant to designs for boosted fission weapons
< 1 t (likely to remain undetected)	• Building experience and confidence with weapons physics experiments	• One-point safety tests • Validation of some unboosted fission weapon designs • Address some stockpile and design code issues
1 t–100 t (may not be detectable, but strongly location dependent without evasion)	• One-point safety tests • Pursue unboosted designs***	• Develop low-yield weapons (validation of some unboosted fission weapon designs with yield well below a kiloton) • Possible overrun range for one-point safety tests
100 t–1 kt likely to be detected without evasion, reduced probability of detection with evasion (but strong location dependence)	• Pursue improved implosion weapon designs • Gain confidence in certain small nuclear designs	• Proof tests of compact weapons with yield up to 1kt • Validate some untested implosion weapon designs • Assess stockpile issues and validate some design codes
1 kt–10 kt unlikely to be concealable	• Begin development of low-yield boosted fission weapons • Eventual development and full testing of some implosion weapons and low-yield thermonuclear weapons • Eventual proof tests of fission weapons with yield up to 10 kt	• Development of low-yield boosted fission weapons • Development and full testing of some implosion weapons and low-yield thermonuclear weapons • Proof tests of fission weapons with yield up to 10 kt
> 10 kt not concealable	• Eventual development and full testing of boosted fission weapons and thermonuclear weapons or higher- yield unboosted fission weapons	• Development and full testing of new configurations of boosted fission weapons and thermonuclear weapons • Pursue advanced strategic weapons concepts (e.g., EMP)

Notes: * In this column the committee summarizes the current state of technology for detecting underground nuclear explosions. This summary does not represent any particular sensor network, medium, or location. For example, IMS detection capabilities can be substantially better than what appears in the column for some locations, and detection capability has generally improved over time.

** That is, lacking an adequate combination of nuclear-test data, advanced instrumentation, and sophisticated analytical techniques, and without having received assistance in the form of transfer of the relevant insights.

*** Limited improvements of efficiency and weight of unboosted fission weapons compared to 1st generation weapons not needing testing (NRC, 2002. p. 68)

SOURCE: Committee

Finding 4-11: The value of low-yield evasive underground testing to a particular country depends on that country's nuclear-explosion test experience and/or design sophistication.

- **Nuclear Weapon States could use low-yield evasive testing to partially validate design codes and modernize their arsenals.**
- **Countries with lesser test experience could build confidence with weapons physics experiments or develop and certify inefficient, unboosted fission weapons that might pose a regional threat.**

Because such tests may be undetectable, these advances could be made whether or not the CTBT were in force.

Finding 4-12: Russia and China are unlikely to be able to deploy new types of strategic nuclear weapons that fall outside of the design range of their nuclear-explosion test experience without several multi-kiloton tests to build confidence in their performance. Such multi-kiloton tests would likely be detectable (even with evasion measures) by appropriately resourced U.S. national technical means and a completed IMS network.

Finding 4-13: Other States intent on acquiring and deploying modern, two-stage thermonuclear weapons would not be able to have confidence in their performance without multi-kiloton testing. Such tests would likely be detectable (even with evasion measures) by appropriately resourced U.S. national technical means and a completed IMS network.

5

COMPLETE LIST OF FINDINGS AND RECOMMENDATIONS

Chapter 1

Finding 1-1: The technical capabilities for maintaining the U.S. stockpile absent nuclear-explosion testing are better now than anticipated by the *2002 Report*.

Finding 1-2: Future assessments of aging effects and other issues will require quantities and types of data that have not been provided by the surveillance program in recent years.

Finding 1-3: The committee judges that Life-Extension Programs (LEPs) have been, and continue to be, satisfactorily carried out to extend the lifetime of existing warheads without the need for nuclear-explosion tests. In addition to the original LEP approach of *refurbishment*, sufficient technical progress has been made since the *2002 Report* that *re-use* or *replacement* of nuclear components can be considered as options for improving safety and security of the warheads.

Finding 1-4: Provided that sufficient resources and a national commitment to stockpile stewardship are in place, the committee judges that the United States has the technical capabilities to maintain a safe, secure, and reliable stockpile of nuclear weapons into the foreseeable future without nuclear-explosion testing. Sustaining these technical capabilities will require at least the following:

- *A Strong Scientific and Engineering Base*. There must be continued adherence to the principle that the ability to assess and certify weapons rests on technical understanding of weapons phenomena, data from past nuclear-explosion tests, computations, and data from past and ongoing experiments. Maintaining both a strategic computing capability and modern non-nuclear-explosion testing facilities (for hydrodynamic testing, radiography, material equation-of-state measurements, high explosives testing, and fusion testing) is essential for this purpose.
- *A Vigorous Surveillance Program*. An intensive surveillance program aimed at discovering warhead problems is crucial to the health of the stockpile.
- *Adequate Ratio of Margin to Uncertainty.* Performance margins that are sufficiently high, relative to uncertainties, are key ingredients of confidence in weapons performance.[1]
- *Modernized Production Facilities.* Most of the nuclear weapons production facilities are old (50 years in some cases) and are both difficult and costly to operate in accordance with modern standards of safety and security.
- *A Competent and Capable Workforce.* Nuclear weapons work (e.g., the SSP) is key to meeting a range of challenges in the broader national security landscape. Exploration of these broader areas (e.g., nonproliferation programs, render safe,

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[1] Some of today's systems already have relatively high margin-to-uncertainty ratios; others are relatively low.

etc.) can provide opportunities for intellectual stimulation and professional development that will attract a diverse, capable workforce. It is equally important to ensure that the Department of Defense, particularly the Defense Threat Reduction Agency, the Navy's Strategic Systems Project Office, and the Air Force's Ballistic Missile Organization maintains a technically competent workforce (Congressional Commission, 2009; U.S. Secretary of Defense Task Force on DOD Nuclear Weapons Management, 2008; Defense Science Board, 2008).

Recommendation 1-1: To address each of the essential elements of stockpile stewardship listed in Finding 1-4, NNSA, working with the Administration and Congress as appropriate, should:

- *Maintain a continuing dynamic of experiments linked with analysis.* Both are essential to maintaining the capability to render judgments about stockpile issues.
- *Maintain a vigorous surveillance program* that is systematic; is statistically based where possible; and continuously reflects lessons learned from annual surveillance, LEPs, fixing problems, and science-based analysis. Nondestructive tools and experimentally validated computational analysis should be developed and applied to introduce more predictive capability into the surveillance system.
- *As part of each LEP, explore options for achieving adequate margins* through reuse or replacement scenarios in addition to refurbishment, to determine how best to meet military, technical, and policy objectives. Assess uncertainties associated with each scenario.
- *Develop and implement a long-term production facility modernization plan.* This should include maintaining a plutonium science and production capability, including the ability to produce various types of pits for weapons in the stockpile.
- *Broaden the base of its nuclear expertise by involving nuclear-capable personnel in related national security projects* (nuclear forensics, intelligence, threat reduction programs, basic science applications of stewardship activities, etc.).

Finding 1-5: To maintain a test readiness capability of 24-36 months as required by PDD-15, some test readiness capabilities must be explicitly maintained in addition to the Stockpile Stewardship Program. Test Readiness draws on SSP capabilities but requires a suitable test site, a set of specialized equipment and infrastructure, and a body of specialized knowledge. The pacing item in resuming nuclear explosive testing may be regulatory rather than technical.

Recommendation 1-2: To maintain a test readiness posture of 24-36 months, NNSA should:

- Preserve the Nevada Test Site's ability to host a nuclear-explosion test;
- Support the containment capability unique to underground nuclear-explosion testing;
- Maintain seismic data necessary to meet U.S. obligations under the Threshold Test Ban Treaty should testing resume;
- Maintain the radiochemistry laboratory infrastructure and drill-back capability;
- Support fast readout requirements and prompt diagnostic equipment;
- Maintain a library that includes testing methods, containment rack designs, procedures, processes; and other relevant information;
- Maintain nuclear-certifiable emplacement cranes;
- Maintain field-test neutron generators;

- Establish a process for obtaining waivers from health and environmental regulations if required, but, given the frequency with which laws change, do not seek such waivers in advance.

NNSA should include all of these elements within the SSP and evaluate their status as part of the annual assessment of the fulfillment of safeguards recommended in Chapter 3 of this report.

Chapter 2

Finding 2-1: U.S. National Technical Means provide monitoring capability that is superior to that of the CTBTO, but the use of U.S. NTM for diplomatic purposes may be constrained due to its largely classified nature.

Finding 2-2: The International Monitoring System provides valuable data to the United States, both as an augmentation to the U.S. NTM and as a common baseline for international assessment and discussion of potential violations when the United States does not wish to share NTM data.

Recommendation 2-1: The United States should support both the completion of the IMS and its operations, training, and maintenance, whether or not the CTBT enters into force.

Finding 2-3: Independent of the CTBT, the national security interests of the United States and its allies require the seismic monitoring of foreign nuclear-explosion tests.

Finding 2-4: Technical capabilities for seismic monitoring have improved substantially in the past decade, allowing much more sensitive detection, identification, and location of nuclear events. More work is needed to better quantify regional monitoring identification thresholds, particularly in regions where seismic waves are strongly attenuated.

Recommendation 2-2: AFTAC should study the extent to which detection thresholds could be improved by making fuller use of the authenticated data from the IMS as well as targeted use of calibrated non-IMS seismic stations to help characterize special events of high concern.

Recommendation 2-3: To meet its national security needs, the United States should continue to enhance and sustain its NTM seismic monitoring capabilities.

Finding 2-5: One of the major advances in monitoring in the last 10 years is that most of the IMS seismic stations are operating now, and most of those have been certified for data quality (including calibration) and integrity (with respect to tampering and data authenticity). The threshold levels for IMS seismic detection are now well below 1 kt worldwide for fully coupled explosions.

Finding 2-6: Seismic technologies for nuclear monitoring have the potential to improve event detection, location, and identification substantially over the next years to decades.

Recommendation 2-4: The United States should renew and sustain investment in seismic R&D efforts to reap the rewards of new methodologies, source models, Earth models,

and data streams to enhance underground nuclear explosion monitoring, regardless of the status of CTBT ratification.

Finding 2-7: Closer collaboration among the U.S. monitoring, NTM, national laboratory, and academic communities would help the United States keep up with new developments and technologies for seismic nuclear-explosion test monitoring.

Finding 2-8: AFTAC has demonstrated notable achievements over the past decade, including major enhancements in all aspects of radionuclide monitoring.

Recommendation 2-5: The United States should continue to actively support radionuclide collection, including R&D activities to better discriminate nuclear-test signature radionuclides from background, thus improving the ability to detect well-contained and lower-yield nuclear-explosion tests.

Finding 2-9: In the past 10 years, the IMS radionuclide network has gone from being essentially non-existent to a nearly fully functional and robust network with new technology that has surpassed most expectations.

Finding 2-10: The IMS has made significant improvements in data processing.

Finding 2-11: Ongoing measurement and understanding of global backgrounds of radionuclides relevant to nuclear-explosion monitoring are critical for improving radionuclide detection.

Recommendation 2-6: The United States should support research needed to understand the global background of radionuclides.

Finding 2-12: In at least 50 percent of nuclear-explosion tests near 1 kt or larger, even those carried out by experienced testers, xenon noble gases may be detectable offsite above the detection limits of the IMS (0.1 to 0.2 mBq/m^3) from prompt venting of nuclear-explosion tests; also, long-term seepage of appreciable noble gases would be expected that could be detectable, both offsite and onsite.

Finding 2-13: The IMS detection threshold for in-water explosions is 10 tons (0.01 kt) or below worldwide and below 1 ton (<0.001 kt) throughout the majority of the world's oceans.

Finding 2-14: As of 2010, two of the six hydroacoustic stations of the IMS were damaged and became non-operational after installation and certification; one will be restored.

Recommendation 2-7: The U.S. should assess the need for data from the damaged hydroacoustic stations and, if appropriate, work with the CTBTO to restore these stations to operational capability.

Finding 2-15: Infrasound detection is a valuable approach for monitoring atmospheric nuclear explosions.

Finding 2-16: Integration of infrasound with seismic data and analysis will provide better detection, location, and identification of explosions.

Finding 2-17: Sustainment of the U.S. satellite monitoring capability to detect any nuclear explosion in the atmosphere or space, whatever its origin, will continue to be in the interest of the United States and its allies, regardless of whether the CTBT enters into force.

Recommendation 2-8: Enhanced satellite nuclear detonation detection systems should be deployed in upgrades to GPS (GPS Block IIF and Block III) and the follow-on to DSP, the Space-Based Infrared System (SBIRS). Provision for adequate ground-based data processing is also essential. Decisions regarding whether and at what level to maintain the satellite nuclear detonation detection capability should be made as part of high-level national security policy and acquisition assessments.

Finding 2-18: Although the IMS is operating effectively, meeting the needs of CTBT entry into force will require more staff and easing of budgetary constraints.

Recommendation 2-9: The United States and others should ensure that priorities and funds are sufficient for IMS to meet ongoing needs, including after entry into force.

Finding 2-19: A technical exercise that tests the advantages of incorporating auxiliary seismic station data into the CTBTO's automated system would be useful to demonstrate the feasibility of this proposed improvement.

Finding 2-20: Location accuracy of events identified with waveform signals (seismic, hydroacoustic or infrasound) can be improved technically by better calibration to reduce the size of error ellipses and to improve detection and location accuracy. A technical review that evaluates calibration efforts, such as station tuning, phase labeling, and location accuracy, could identify ways to improve absolute location accuracy.

Finding 2-21: The CTBTO benefits from systematic, sustained interaction with the broader scientific communities involved in areas relevant to its mission.

Finding 2-22: A CTBTO on-site inspection (OSI) would have a high likelihood of detecting evidence of a nuclear explosion with yield greater than about 0.1 kilotons, provided that the event could be located with sufficient precision in advance and that the OSI was conducted without hindrance.

Finding 2-23: There are many opportunities for confidence-building measures to support nuclear explosion monitoring, particularly through engaging scientists and engineers in cooperative efforts.

Recommendation 2-10: The United States should pursue bilateral (and, to the extent justified and politically feasible, limited multilateral) programs of scientific cooperation for purposes of confidence building in support of monitoring nuclear explosions. These programs should be periodically reviewed for effectiveness and for appropriate controls on information.

Finding 2-24: Test-site transparency agreements can provide a mechanism for mitigating concerns about very-low-yield testing (yields up to about 1 ton).

Chapter 3

Finding 3-1: A decreasing fraction of the budget for the nuclear weapons program is available for the actual technical work that must be accomplished to sustain the U.S. deterrent.

Finding 3-2: A strong national commitment to recruiting and sustaining a high-quality workforce; recapitalizing aging infrastructure and force structure; and strengthening the science, engineering, and technology base is essential to sustaining a safe, secure, and reliable stockpile, as well as necessary explosion-monitoring capability for the United States.

Recommendation 3-1: The Administration, in concert with Congress, should formulate and implement a comprehensive plan that provides a clear vision and strategy for maintaining the nation's nuclear deterrence capabilities and competencies, as recommended in the 2010 Nuclear Posture Review and related studies.

Finding 3-3: The current contract system for the nuclear weapons laboratories has not produced a more innovative, efficient, and cost-effective approach to carrying out the tasks of the nuclear weapons program. Rather, there is evidence that the present system acts as a significant barrier to many of the objectives delineated in this report.

Recommendation 3-2: The DOE/NNSA should re-evaluate the current contract system for carrying out the tasks of the nuclear weapons program. At a minimum, any new approach should:

- **Reduce the number of requirements in directives and simultaneously transform those requirements to performance goals (prescribing what must be done, not how to do it).**
- **Shift the balance of incentives in contracts for the weapons laboratories to emphasize successful implementation of the technical mission.**

Finding 3-4: Technical improvements needed for monitoring the CTBT (and other treaties) would benefit greatly from better access to skilled personnel and computational and experimental facilities at the national labs. This access is needed by agencies with CTBT monitoring and verification responsibilities.

Recommendation 3-3: Provisions of a recently-agreed-to governance charter should be implemented to enable better access to skilled personnel and capabilities at the national labs by agencies other than DOE/NNSA. Such access will directly benefit research and technology development aimed at improving CTBT (and other treaty) monitoring and verification.

Finding 3-5: Air Force Research Laboratory (AFRL) funding for nuclear explosion-monitoring R&D is significantly lower than in past decades, whereas the monitoring task has become far more complicated.

Recommendation 3-4: For the United States to monitor effectively for the possibility of nuclear-test explosions, the U.S. Government should fund a robust R&D program to maintain ongoing operational capabilities and to support achievable improvements.

Finding 3-6: Continued enhancement of the USAEDS is necessary to monitor the CTBT. Research and development of advanced monitoring capabilities are needed, including research and training at universities of the next generation of scientists and engineers.

Recommendation 3-5: A sustained, predictable program of investment in nuclear-explosion monitoring R&D should be coordinated among the responsible U.S. agencies. This program should specifically include investments in university research and training programs focused on technical disciplines critical for treaty monitoring.

Finding 3-7: Year-to-year funding for the Ground-Based Nuclear Explosion Monitoring (GNEM) R&D program has decreased in recent years. The decline of funding for university research is jeopardizing R&D and training of the next generation of researchers.

Recommendation 3-6: The DOE/NNSA Ground-Based Nuclear Explosion Monitoring (GNEM) Program merits sustained, predictable funding, including funding for university investments through a competitive, peer-reviewed process.

Finding 3-8: Planned enhancements to the U.S. satellite nuclear detonation detection capability are necessary to adequately monitor the CTBT. Even without the CTBT, these enhancements to the USNDS capability are important to maintaining and improving the USAEDS.

Recommendation 3-7: The DOE/NNSA and the U.S. Air Force joint satellite-based monitoring program (USNDS) should continue planned enhancements needed to monitor the CTBT through 2020 and beyond. Advanced technology R&D should continue to enable future enhancements and anticipate surprise.

Finding 3-9: The current budget for the IMS allows operating its stations on a 24/7 basis; however, the stations are operating on a provisional basis, without weekend and emergency support contracts. The International Data Centre (IDC), now staffed for a limited number of hours each weekday, would have to move to 24/7 operation under CTBT entry into force.

Recommendation 3-8: The United States should support the CTBTO in its annual assessed and voluntary contributions to ensure that the IMS is fully installed and, with the IDC, is ready to meet CTBT entry-into-force obligations, including support for operating costs and long-term maintenance and repair of monitoring stations.

Finding 3-10: The OSI capability of the CTBTO lags behind the readiness of the IMS; however, steps have been taken, such as the 2008 Integrated Field Exercise, which have improved OSI capabilities significantly.

Recommendation 3-9: The United States should support the CTBTO OSI work by participating fully in all of its aspects, including training and field exercises.

Finding 3-11: Without agile production capabilities, it is not possible to promptly correct deficiencies revealed by surveillance or to remanufacture components or weapons when required.

Recommendation 3-10: The U.S. CTBT safeguards should include the maintenance of adequate production and non-nuclear-explosion testing facilities.

Finding 3-12: There is currently no mechanism that would enable Congress to assess whether the U.S. CTBT safeguards were being fulfilled after entry into force.

Recommendation 3-11: Under the CTBT, the Administration should prepare an annual evaluation of the ongoing effectiveness of safeguards and formally transmit it to Congress.

Chapter 4

Finding 4-1: The Nuclear Weapon States have been able to maintain their nuclear weapons programs under a nuclear-explosion-test moratorium and are likely to be able to make nuclear weapons modifications that fall within the design range of their test experience without resorting to nuclear-explosion testing.

Finding 4-2: Hydronuclear tests would be of limited value in maintaining the United States nuclear weapon stockpile in comparison with the advanced tools of the Stockpile Stewardship Program.

Finding 4-3: Based on Russia's extensive history of hydronuclear testing, such tests could be of some benefit to Russia in maintaining or modernizing its nuclear stockpile. However, it is unlikely that hydronuclear tests would enable Russia to develop new strategic capabilities outside of its nuclear-explosion test experience.

Finding 4-4: An evader determined to avoid detection would test at levels the evader believes would have a low probability of detection.

Finding 4-5: Mine masking is a less credible evasion scenario than it was at the time of the *2002 Report* because of improvements in monitoring capabilities.

Finding 4-6: With the inclusion of regional monitoring, improved understanding of backgrounds, and proper calibration of stations, an evasive tester in Asia, Europe, North Africa, or North America would need to restrict device yield to levels below 1 kiloton (even if the explosion were fully decoupled) to ensure no more than a 10 percent probability of detection for IMS and open monitoring networks.

Finding 4-7: For IMS and open monitoring networks, methods of evasion based on decoupling and mine masking are credible only for device yields below a few kilotons worldwide and at most a few hundred tons at well-monitored locations.

Finding 4-8: The States most capable of carrying out evasive nuclear-explosion testing successfully are Russia and China. Countries with less nuclear-explosion testing experience would face serious costs, practical difficulties in implementation, and uncertainties in how effectively a test could be concealed. In any case, such testing is unlikely to require the United States to return to nuclear-explosion testing.

Finding 4-9: Better technical understanding of the decoupling process in various types of geologies would likely improve the capability to detect evasive nuclear-explosion testing.

Recommendation 4-1: If the possibility of evasive nuclear-explosion testing through cavity decoupling continues to be a concern, the United States should:
- **Apply modern computational and experimental methods to understand the decoupling process in various geologies;**
- **Identify areas such as geologic salt domes advantageous for decoupling and consider the need for additional monitoring; and**
- **Identify indicators that a country is using—or may be planning to use—decoupling as an evasion strategy.**

Finding 4-10: Threats could arise from clandestine nuclear weapons activity. For instance, a country with no testing experience and a modest industrial base could confidently build and deploy a single-stage, unboosted nuclear weapon without any testing, if it had access to sufficient quantities of fissile material. These advances could be made whether or not the CTBT were in force. However, it is highly likely that the United States could counter these threats without returning to nuclear-explosion testing and thus could respond equally well whether or not the CTBT were in force.

Finding 4-11: The value of low-yield evasive underground testing to a particular country depends on that country's nuclear-explosion test experience and/or design sophistication.
- **Nuclear Weapon States could use low-yield evasive testing to partially validate design codes and modernize their arsenals.**
- **Countries with lesser test experience could build confidence with weapons physics experiments or develop and certify inefficient, unboosted fission weapons that might pose a regional threat.**

Because such tests may be undetectable, these advances could be made whether or not the CTBT were in force.

Finding 4-12: Russia and China are unlikely to be able to deploy new types of strategic nuclear weapons that fall outside of the design range of their nuclear-explosion test experience without several multi-kiloton tests to build confidence in their performance. Such multi-kiloton tests would likely be detectable (even with evasion measures) by appropriately resourced U.S. national technical means and a completed IMS network.

Finding 4-13: Other States intent on acquiring and deploying modern, two-stage thermonuclear weapons would not be able to have confidence in their performance without multi-kiloton testing. Such tests would likely be detectable (even with evasion measures) by appropriately resourced U.S. national technical means and a completed IMS network.

APPENDIX A

Committee on Reviewing and Updating "Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty" (CTBT)

Committee Member Biographies

Ellen D. Williams (NAS), Chair, is the Chief Scientist at BP, where she is responsible for long-range scientific advice and planning. Prior to joining BP, she worked for over thirty years in academia, obtaining her Ph.D at Caltech in 1981 and then moving to the University of Maryland, where she became a Distinguished University Professor in the Institute of Physical Science and Technology and the Department of Physics in 2000. Her research specialty in nanoscience lies at the intersection of physics, chemistry and materials science. In support of her research interests, in 1996 she founded the University of Maryland Materials Research Science and Engineering Center and served as its director for 15 years. In parallel, she has worked extensively in providing technical advice to the U.S. government, primarily through the Departments of Energy and Defense, including service on the Congressional Committee to Review the Strategic Posture of the United States. Dr. Williams has published widely in her research specialty and has served on a large number of professional committees and editorial boards. She is a member of the National Academy of Sciences; is a fellow of the American Physical Society, American Vacuum Society and American Academy of Arts and Sciences; and has been recognized by awards from the Japan Society for the Promotion of Science, the American Physical Society, and the Materials Research Society.

Marvin L. Adams is HTRI professor of nuclear engineering and Director of the Institute for National Security Education and Research at Texas A&M University. He earned his B.S from Mississippi State University in 1981, his M.S. from the University of Michigan in 1984, and his Ph.D. from the University of Michigan in 1986, all in nuclear engineering. From 1977 to 1982, he worked at Tennessee Valley Authority's Sequoyah Nuclear Plant and its support office. He joined Lawrence Livermore National Laboratory in 1986. He left Livermore in 1992 for the faculty position that he continues to hold at Texas A&M University. In 2006–2007, he directed the Center for Large-scale Scientific Simulation at Texas A&M, and from 2005 until 2009, he served as Associate Vice President for Research. He has served as a consultant to Lawrence Livermore National Laboratory, Sandia National Laboratories, Los Alamos National Laboratory, and the Mitre Corporation. Dr. Adams has authored or co-authored more than 100 research publications, most in the area of computational science and engineering, and he is a Fellow of the American Nuclear Society.

Theodore (Ted) Bowyer is an AAAS Fellow and a Laboratory Fellow/program manager in the area of nuclear explosion monitoring and policy support at the Pacific Northwest National Laboratory. In 1994, he received a Ph.D. in nuclear physics from Indiana University and since that time has worked at PNNL in a variety of nonproliferation programs related to nuclear weapons material production detection, nuclear testing detection, and nonproliferation policy. He spent several years in the Office of Nonproliferation Policy at DOE/NNSA where he served as a scientific advisor on the Comprehensive Nuclear Test Ban Treaty and related Nuclear

Testing Limitations treaties and agreements, as well as the Fissile Material Cutoff Treaty. Dr Bowyer has spent significant time serving the U.S. Delegations to the Conference on Disarmament in Geneva and CTBT Working Group B (WGB) in Vienna as a technical advisor. Currently, Dr. Bowyer serves as the chair of the CTBT WGB Radionuclide Expert Group and chair of the U.S. Radionuclide Subgroup of the Verification Monitoring Task Force. Ted Bowyer's research interests include radioactive noble gas measurements, nuclear forensics, and nuclear detector development, including the design of the U.S. Automated Radioxenon Sampler-Analyzer (ARSA), which received the Federal Laboratory Consortium award in 2001.

Linton F. Brooks served from July 2002 to January 2007 as Administrator of the U.S. Department of Energy's National Nuclear Security Administration, where he was responsible for the U.S. nuclear weapons program and for the Department of Energy's international nuclear nonproliferation programs. He has five decades of experience in national security, including service as Assistant Director of the Arms Control and Disarmament Agency, Chief U.S. Negotiator for the Strategic Arms Reduction Treaty, Director of Defense Programs and Arms Control on the National Security Council staff, Vice President for Policy Analyses at the Center for Naval Analyses and a number of Navy and Defense Department assignments as a 30-year career naval officer. Currently he is an independent consultant on national security issues, a Senior Advisor at the Center for Strategic and International Studies, a Distinguished Research Fellow at the National Defense University, and an advisor to two of the Department of Energy weapons laboratories. Ambassador Brooks holds degrees in physics from Duke University and in government and politics from the University of Maryland and is a Distinguished Graduate of the U.S. Naval War College.

Donald D. Cobb held several technical staff and management positions at Los Alamos National Laboratory (LANL) beginning in 1976, including Division Leader for Space Science and Technology, Division Leader of Nonproliferation and International Security Division, and Associate Director for Threat Reduction. In 2004, he was named Deputy Director responsible for oversight of all LANL operations pending the transition of the University of California's Laboratory management contract. Dr. Cobb retired from the University of California in 2006 and remains as a guest scientist at LANL. During his 30 years of experience in nuclear safeguards and weapon phenomenology, Dr. Cobb conducted research on the detection of atmospheric nuclear detonations and led designs of safeguards systems for nuclear power facilities. As project leader for the successful Beam Experiments Aboard Rocket (BEAR) experiment (1989), Dr. Cobb received a Laboratory Distinguished Performance Award and certificate of merit from the Department of Defense Strategic Defense Initiative Office. In 1991, he spent a year assigned at the Department of Energy's Office of Space in Washington, D.C. In 1998–2000, he served as a member of the New Mexico Governor's Space Commission. In 2002, he was a member of the Defense Science Board task force on nuclear threats. In 2006, Dr. Cobb was awarded the U.S. Department of Energy National Nuclear Security Administration's Gold Medallion, its highest award for exceptional service. He is currently employed by the Department of Defense as a Highly Qualified Expert (nonproliferation and arms control) and serves as a senior advisor to the Director, Department of Defense Threat Reduction Agency. Dr. Cobb is a member of the University of New Mexico Space Technology and Applications International Forum steering committee, the American Physical Society, and the American Association for the Advancement of Science. He received a Bachelor of Science degree in physics from Northern Illinois University and a Master of Science and Ph.D. in theoretical nuclear physics from the University of Iowa. He currently serves on the boards of the United Way/Northern New Mexico and the LANL Foundation.

Richard L. Garwin (NAS/NAE/IOM) received his B.S. in physics from Case Institute of Technology, Cleveland, in 1947, and his Ph.D. in physics from the University of Chicago in 1949. He is IBM Fellow Emeritus at the Thomas J. Watson Research Center, Yorktown Heights, New York. After three years on the faculty of the University of Chicago, he joined IBM Corporation in 1952. Until June 1993 he was IBM Fellow at the Thomas J. Watson Research Center, Yorktown Heights, New York and Adjunct Professor of Physics at Columbia University. In addition, he is a consultant to the U.S. government on matters of military technology, arms control, and other security matters. He has been Director of the IBM Watson Laboratory, Director of Applied Research at the IBM Thomas J. Watson Research Center, and a member of the IBM Corporate Technical Committee. He has also been Professor of Public Policy in the Kennedy School of Government, Harvard University. He has made contributions in the design of nuclear weapons, in instruments and electronics for research in nuclear and low-temperature physics, in the establishment of the non conservation of parity and the demonstration of some of its striking consequences, in computer elements and systems (including superconducting devices) in communication systems, in the behavior of solid helium, in the detection of gravitational radiation, and in military technology. He has published more than 500 papers, has been granted 46 U.S. patents, and is coauthor of many books. He was a member of the President's Science Advisory Committee 1962-1965 and 1969-1972, and of the Defense Science Board 1966–69. He is a Fellow of the American Physical Society, IEEE, and American Academy of Arts and Sciences, and is a member of the National Academy of Sciences, the Institute of Medicine, the National Academy of Engineering, the Council on Foreign Relations, the International Institute of Strategic Studies, and the American Philosophical Society. From 2001 to 2008, he chaired Department of State's Arms Control and Nonproliferation Advisory Board. In 2002, he was elected for a second three-year term to the Council of the National Academy of Sciences. He is a member of the Committee on International Security and Arms Control of the National Academies of Science. He has received several awards from the U.S. Government, including the R.V. Jones Award for Scientific Intelligence, the Enrico Fermi Award, and the National Medal of Science (nuclear weapons design; stockpile stewardship).

Raymond Jeanloz (NAS) is a professor of Earth and Planetary Science and of Astronomy at the University of California at Berkeley. He currently chairs the National Academy of Sciences' Committee on International Security and Arms Control; previously chaired the National Research Council's Board on Earth Sciences and Resources; and has served as an adviser to the Department of Energy, National Science Foundation, and NASA, as well as the Directors of Los Alamos and Lawrence Livermore National Laboratories. His work, including scientific research on the properties of materials at high pressures and temperatures and on the constitution and evolution of planetary interiors, has been recognized through fellowship in the American Academy of Arts and Sciences, American Association for the Advancement of Science, American Geophysical Union and American Physical Society; membership in the National Academy of Sciences; and a MacArthur Prize Fellowship. After completing his bachelor's degree (Amherst College, 1975), he received his Ph.D. from the California Institute of Technology in 1979 and joined the faculty of Harvard University before moving to UC Berkeley in 1981.

Richard W. Mies, Admiral, US Navy (retired), is the CEO and President of The Mies Group, Ltd. and provides strategic planning and risk assessment advice and assistance to clients on international security, energy, defense, and maritime issues. A distinguished graduate of the US Naval Academy, he completed a 35-year career as a nuclear submariner in the U.S. Navy and commanded U.S. Strategic Command for four years prior to retirement in 2002. Admiral Mies served as a Senior Vice President and Deputy Group President of Science Applications International Corporation (SAIC) and as the President and Chief Executive Officer of Hicks and

Associates, Inc, a wholly owned subsidiary of SAIC from 2002 to 2007. He also served as the Chairman of the Department of Defense Threat Reduction Advisory Committee from 2004 to 2010. He presently serves as the Chairman of the Boards of the Navy Mutual Aid Association and the Naval Submarine League and as the Chairman of the Strategic Advisory Group of US Strategic Command. He is a member of the Committee on International Security and Arms Control of the National Academy of Sciences; a member of the Boards of Governors of Los Alamos National Laboratory and Lawrence Livermore National Laboratory; and a member of the Board of Directors of Mutual of Omaha Company, Babcock and Wilcox Company, and Exelon Corporation. He also serves on numerous advisory boards. Admiral Mies completed post-graduate education at Oxford University, the Fletcher School of Law and Diplomacy, and Harvard University. He holds a Masters degree in government administration and international relations.

C. Bruce Tarter is the Director Emeritus of the University of California Lawrence Livermore National Laboratory and was the eighth director to lead the Laboratory since it was founded in 1952. A theoretical physicist by training and experience, he has spent most of his career at the Laboratory. As director, he led the Laboratory in its mission to ensure national security and apply science and technology to the important problems of our time. He received a bachelor's degree in physics from the Massachusetts Institute of Technology and a Ph.D. from Cornell University. His career at the Livermore Laboratory began in 1967 as a staff member in the Theoretical Physics Division. He led the Laboratory through the transition to a post-Cold War nuclear weapons world, helping to set the foundation for current programs in stewardship of the U.S. nuclear stockpile. He also worked to build the programs in nonproliferation and counter-terrorism, and in energy, environment, and bioscience. Tarter has served in a number of outside professional capacities, including a six-year period with the Army Science Board; service as an adjunct professor at the University of California, Davis; membership on the California Council on Science and Technology, the Laboratory Operations Board (Secretary of Energy Advisory Board), the Council on Foreign Relations, the Defense Science Board, the Congressional Commission on the Strategic Posture of the United States, and Draper Laboratory (member of the Corporation and the Board of Directors). He is a Fellow of the American Physical Society and the American Association for the Advancement of Science and received the Roosevelt's Gold Medal Award for Science (1998), NNSA Gold Medal for Distinguished Service (2002), and U.S. Department of Energy Secretary's Gold Award (2002).

Subcommittee on Seismology: In Support of the Committee on Reviewing and Updating "Technical Issues Related to the Comprehensive Nuclear-Test-Ban Treaty" (CTBT)

Subcommittee Member Biographies

Lynn R. Sykes (NAS), Subcommittee Chair, is the Higgins Professor Emeritus, Department of Earth and Environmental Sciences, Lamont-Doherty Earth Observatory, Columbia University. He received his Bachelor of Science, Massachusetts Institute of Technology, 1960; Master of Science, Massachusetts Institute of Technology, 1960; and Ph.D., Columbia University, 1965. His research interests include: earthquake studies, control of nuclear weapons, tectonics, and natural hazards. Of particular relevance to the study, he has worked on topics that have significant scientific and public policy components such as large earthquakes in California and Alaska, the causes of earthquakes in plate interiors such as the eastern United States, natural and technological hazards and disasters, and the Comprehensive Nuclear Test Ban Treaty. He is known for using seismic and other data from the Earth sciences to characterize earthquakes and explosions. Dr. Sykes has authored or coauthored more than 140 scientific papers, about 40 of which are in the area of the verification of nuclear testing, and he was a member of the U.S. delegation that negotiated the Threshold Test Ban Treaty with the USSR in 1974. In addition to being a member of the U.S. National Academy of Sciences, he is a member of the American Academy of Arts and Sciences and in 2000 received the Vetelesen Award along with Walter Pitman and Jason Morgan for contributions to the development of plate tectonics.

Hans Hartse has been a research seismologist at Los Alamos National Laboratory since 1992. His areas of expertise include seismic event discrimination at regional and local distances, analyses of mining-related seismicity, seismic coda studies, seismic event location methods, and seismic database construction and exploitation. His studies have primarily focused on Asia with an emphasis on China, Kazakhstan, and Russia. In 2002, he co-edited (with William Walter) a "Pure and Applied Geophysics" special journal volume titled "Seismic Event Discrimination and Identification related to Monitoring a CTBT." He has authored journal articles concerning nuclear explosion event identification at Nevada Test Site, the former Soviet Test Site in Kazakhstan, Russia's Novaya Zemlya Test Site, and China's Lop Nor Test Site. He earned a B.S. in Geophysical Engineering (1982) from Montana Tech, M.S. in Geophysics (1987) from New Mexico Tech, and Ph.D. in Geophysics (1991) from New Mexico Tech, where he studied reflected phases from locally-recorded seismograms associated with the Socorro Magma Body.

Paul G. Richards is Mellon Professor Emeritus of the Natural Sciences, Lamont-Doherty Earth Observatory of Columbia University, and former chairman of Geological Sciences at the university. He served on the original NAS Committee on Technical Issues Related to the CTBT (2000–2003) and on NRC Panels on Seismological Data and Research Requirements for a CTBT (1994–1995; 1995–1997). He was a Foster Fellow at the U.S. Arms Control and Disarmament Agency (1984–1985 and 1993–1994), and during the CTBT negotiations in Geneva he presented an experts paper (1994) for the U.S. on the problems posed by chemical explosions. He spent a sabbatical at Lawrence Livermore National Laboratory (1989–1990). He is co-author of an advanced text (*Quantitative Seismology*) and co-discoverer of seismological evidence that the Earth's inner core has a super-rotation. He is a fellow of the American Geophysical Union and former president of its seismology section. Dr. Richards was elected to the American Academy of Arts and Sciences in 2008 and received the 2009 Harry Fielding Reid medal of the Seismological Society of America.

Gregory van der Vink is President and CEO of Terrametrics LLC, a firm that specializes in poverty reduction and conflict mitigation through environmentally-sustainable economic development and analytical assessments of human responses to environmental change. Prior to Terrametrics LLC, he held senior executive positions in the largest National Science Foundation-funded geoscience research programs. Since 1991, he has also been teaching at Princeton University and currently teaches courses on environmentally-sustainable economic development and environmental entrepreneurship. He was named Princeton's 250th Anniversary Professor for Distinguished Teaching in 2000/2001 and was awarded the Engineering Council's Excellence in Teaching Award in 2004. Dr. van der Vink received his Ph.D. in Geosciences from Princeton University. He has been a National Research Council Postdoctoral Fellow, a Congressional Science Fellow, and an International Affairs Fellow of the Council on Foreign Relations.

William R. Walter is a research geophysicist at the Lawrence Livermore National Laboratory (LLNL) and the LLNL program leader of the DOE/NNSA Office of Nonproliferation and Verification Research & Development (NA-22) funded Ground-based Nuclear Explosion Monitoring (GNEM) and Office of Nonproliferation and International Security (NA-24) funded Nuclear Testing Limitations (NTL) Program. He received a B.A. in Physics from Middlebury College in 1984, and M.S. in Physics from U.C. San Diego in 1986, and a Ph.D. in Geophysics from the University of Nevada, Reno in 1991. In graduate school, he collected and analyzed local seismic data from U.S. nuclear tests in Nevada and the 1988 Soviet Joint Verification Experiment nuclear test in what is now Kazakhstan. He joined LLNL as a postdoc in 1991 and served as the GNEM Identification task leader from 1996 until becoming the LLNL GNEM program leader in 2007. He became the LLNL NTL program leader in 2010. His research interests include geophysics, seismic source physics, earth structure, tectonics, treaty verification and related policy issues. He is the author or co-author of more than 50 peer-reviewed scientific papers.

APPENDIX B

List of CTBT Committee and Seismology Subcommittee Meetings

September 9–10, 2009 CTBT Meeting #1, Washington, DC

Presenters:
Jon Wolfstahl–Office of the Vice President
Thomas D'Agostino–Department of Energy
Ellen Tauscher–Department of State
Ambassador Thomas Graham
Jonathan Medalia–Congressional Research Service
David Hafemeister
Robert Barker, LLNL (retired)
David Albright, ISIS
Raymond Willemann, IRIS
Steve Fetter–Office of Science and Technology Policy

September 29–30, 2009 CTBT Meeting #2, Washington, DC

Presenters:
Don Linger, DTRA Expert
John Murphy, SAIC
John Harvey, DOD
Bradley H. Roberts, DOD
Edward Ifft, Department of State
Kenneth Myers
Peter Nanos
Thomas Chandlee
Stephen Dowling
Michael Edinger
Michael Giltrud
Dimitri Kusnezov (NNSA/DP)
Kevin Greenaugh (NNSA/DP)
George Allen (NNSA/DP)
Randy Bell (NNSA/NA-22)
Michele Smith (NNSA/NA-24)

October 7–9, 2009 CTBT Meeting #3, Site Visit, LLNL

Presenters:
George H. Miller, LLNL
Michael R. Anastasio, LANL
Thomas O. Hunter, SNL
Edward I. Moses, LLNL
Paul Hommert, SNL
Charles F. McMillan, LANL
Bret E. Knapp, LANL
P. Derek Wapman, LLNL
Larry S. Walker, SNL
Bruce T. Goodwin, LLNL
Lorin Benedict, LLNL
Omar A. Hurricane, LLNL
Michael P. Bernardin, LANL
Maurice G. Sheppard, LANL
Charles P. Verdon, LLNL
Mark A. Rosenthal, SNL
Paul Weber, LANL
John J. Zucca, LLNL
Robert M. Heulskamp, SNL
Eric E. Dors, LANL
Dale H. Harling, LLNL
Cary R. Spenser, LLNL
Larry M. Logory, LLNL
Thomas D. Kunkle, LANL
William Tedeschi, SNL

October 21, 2009 **CTBT Meeting #4 and SSC Meeting #1, Site Visit, Patrick Air Force Base (AFTAC)**

Presenters:
Steve Moosman
Directorate of Nuclear Treaty Monitoring
David O'Brien
John W. Roberts, Jr.
Nuclear Debris Collection and Analysis
Research and Evaluation Division

October 22–23, 2009 **CTBT Meeting #5, Washington, DC (briefings with IC, STRATCOM, State Dept., AFTAC)**

October 22, 2009 **SSC Meeting #2, Washington, DC**

November 6, 2009 **SSC Meeting #3, Site Visit, CTBTO, Vienna, Austria**

November 18, 2009 **CTBT Meeting #6, Washington, DC (former lab directors, and others)**

Presenters:
Vic Reis, NNSA
Steve Younger, NNSS
Stephen White, AWE, UK
John Foster
Paul Robinson
James Silk

November 19, 2009 **CTBT Meeting #7, Washington, DC**

December 2–4, 2009 **CTBT Meeting #8, Washington, DC**

January 12–13, 2010 **SSC Meeting #4, Washington, DC**

February 9–10, 2010 **CTBT Meeting #9, Conference Call**

March 11–12, 2010 **CTBT Meeting #10, Washington, DC**

Following the March meeting, the committee held a series of secure teleconferences to refine the text.

November 16–17, 2010 **CTBT Meeting #11, Washington, DC**

December 7–8, 2010 **CTBT Meeting #12, Washington, DC**

January 28, 2011 **CTBT Meeting #13, Washington, DC**

APPENDIX C

The U.S. National Capability to Monitor for Nuclear Explosions

U.S. NTM Improvements in Seismic Detection, 1999–2009

The Air Force Technical Applications Center (AFTAC) provided the committee with information about improvements in seismic monitoring, detection, and identification. Details are discussed in the classified version of this report.

APPENDIX D[1]

Monitoring Areas of High Interest

U.S. National Capabilities in Regions of Interest

Seismic Monitoring Improvements of the Past Decade

Since 1960, a comprehensive program to improve the monitoring of underground testing has been conducted by the United States and has involved the national laboratories, federal agencies, independent contractors, and the academic research community. The effort has produced major advances in all areas—the sensitivity of seismological instrumentation, the methodologies for analyzing the data collected from seismometers, and the geographic distribution of seismological data collections systems.

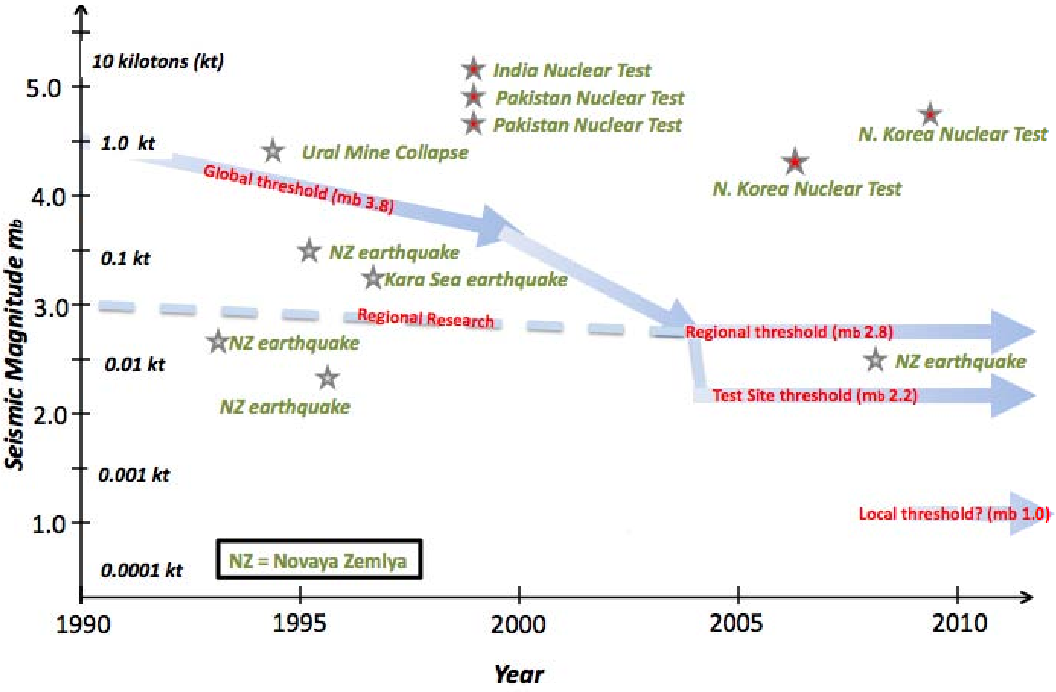

FIGURE D-1: Improvement in seismic monitoring over the last 20 years. Threshold values indicate statistically significant confidence of detection. Note that yield and seismic magnitude scales are logarithmic; each unit of improvement is a factor of ten. Seismic sensitivity to nuclear explosions has improved significantly due to increased deployment of seismometers and improved data analysis. For locations of interest, this allows regional monitoring at distances less than about 1,600 km (1,000 miles), which has a much lower threshold (~ 20 tons or 0.020 kilotons explosive yield) than does global monitoring (~ 200 tons or 0.20 kilotons) recorded at distances typically greater than 2,000 miles. The mention of a "local threshold" lower right in

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[1] This appendix is drawn from the work of the Seismology Subcommittee (see Appendix A), which was directed by the main committee to investigate issues related to seismology and evasion.

figure, refers to the future possibility of bilateral monitoring agreements, distinctly separate from the CTBT. The magnitude estimates listed on this figure are from the IDC and other public sources. SOURCE: Seismology Subcommittee

As depicted in Figure D-1 (and Figure 2-7), over the past decade the capabilities of the U.S. and other countries to detect small tests (and, hence, to detect attempts at evasive testing) have improved greatly due to the implementation of regional monitoring methods, increases in data availability and quality and the application of new discriminants. Fundamental improvements in our ability to monitor underground nuclear testing have occurred in the following three areas:

1. *Use of regional seismic waves*
   The routine use of "regional" waves—seismic waves that travel at higher frequencies within the earth's crust and that travel distances up to 1,600 km (1,000 miles) have fundamentally changed the strategies used for nuclear monitoring. Regional seismic waves travel through the earth's crust and uppermost mantle (the top few tens of kilometers of the earth's interior) at high frequencies. Particularly important is the availability today of data from seismic stations throughout the Middle East, North Africa, Russia, Kazakhstan, Mongolia, China and South Korea. Access to these regions permits countries of special concern to the United States to be monitored at much closer distances and thus down to events of much smaller size. While research into regional seismic methods was underway when the CTBT text was finalized more than a decade ago, it was during the past decade that many of these new research products began to be implemented into the routine operational systems that continue today.

2. *Increased data coverage, quality, and availability*
   Over the last decade, the amount of seismological data that is available to detect nuclear weapons tests (including evasively-conducted tests) has increased approximately 10-fold. Improvements in global digital communication networks have increased the capacity to transmit these large amounts of data from around the world in real or near-real time by approximately 100-fold. Computer power, data storage and retrieval increased approximately 10-fold. Furthermore, much of this newly available data is coming from nations and areas that were previously inaccessible to the United States.

3. *Improvements in our ability to distinguish the seismic signals of a small nuclear explosion from those of naturally occurring earthquakes*
   The use of digital data now provides for ground motion to be recorded continuously with high sampling rates over broad frequency ranges. This has led to new methodologies that use the characteristics of the ground motion that are recorded at various frequencies to distinguish small explosions from naturally occurring earthquakes. Access to high-frequency seismic data has allowed for applications of new discriminants that have improved by about a factor of 10 or more our capability to distinguish explosions from naturally occurring earthquakes. The number of problem events that occur (fewer than about one per year) is now small enough that on-site inspections are feasible under the verification provisions of the treaty.

Monitoring the Russian Test Site at Novaya Zemlya

In ratifying the Threshold Test Ban Treaty with the United States in 1990, the Soviet Union declared two official sites for testing nuclear weapons—eastern Kazakhstan (Semipalatinsk) and Novaya Zemlya. From 1949 to 1989, at which time the Semipalatinsk test site was closed (Adushkin and Leith, 2001), eastern Kazakhstan was the primary location for Soviet nuclear tests. Kazakhstan became an independent country in 1991. The largest Soviet underground nuclear tests, however, were conducted at two sites on remote Novaya Zemlya because they would have produced unacceptable damage in mainland Asia or Europe. The Krasino site on southern Novaya Zemlya has not been used for testing since 1975.

Russia continued testing at its arctic test site near Matochkin Strait on Novaya Zemlya until 1990 (Khalturin et al., 2005). The logistics of work at that site are difficult because its latitude, 73^{o} North, is farther north than the northernmost part of Alaska; 24 hour days of darkness and winter-like cold come early in the Fall. A glacier covers the northern part of the north island of Novaya Zemlya. The containment record of underground nuclear explosions in the hard rock at Novaya Zemlya is poor, with many shots leaking gaseous fission products and particulates (Adushkin and Leith, 2001). Today, much more sensitive measurements of xenon and other noble gases make containment an even more difficult challenge for a potential evader.

A number of public claims have been made about possible Russian testing at Novaya Zemlya since Russia signed the CTBT in September 1996. Seismic monitoring capabilities for the Russian test site on Novaya Zemlya place it among the best-monitored test sites in the world. Novaya Zemlya and its adjacent seas have very low levels of earthquake activity and chemical explosions (Figure D-2). Since 1995 a few small earthquakes on Novaya Zemlya and in the nearby parts of Kara and Barents seas have been claimed in media reports as being problem events (i.e., hard to verify as either explosions or earthquakes. The Seismology Subcommittee examined those claims and concluded that all of those events were small earthquakes (see Sykes, 1997 and the discussion following Figure D-4).

The United States and Norway have worked together for more than 40 years in deploying seismic arrays for monitoring seismic activity on and near Novaya Zemlya and in developing better seismic methods for detection and identification. Data are available in real time from array stations in northern and southern Norway, Spitsbergen (a Norwegian island), and Finland (Figure D-3) and arrays in other parts of Europe. With short time delays, data are available from other stations in Scandinavia and Finland, including the IMS auxiliary station Hagfors in Sweden. The detection capability for the four arrays in Figure D-3, when their continuous data streams are used for analysis, is better than that of the IMS because the station SPITS is only an auxiliary IMS array. Thus, even though it is usually the most sensitive station for signals from Novaya Zemlya, it can only be used by the IMS for signals from events already detected by the other arrays. SPITS is particularly useful for locating Novaya Zemlya events because its azimuthal coverage for that region is so different from that of the other arrays.

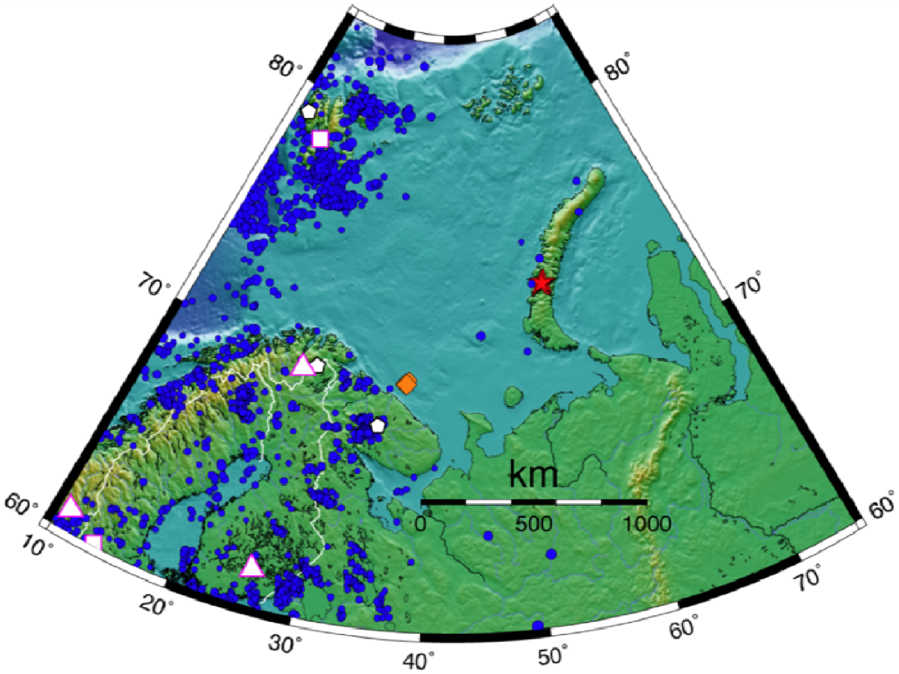

FIGURE D-2: Location of seismic events and stations in the vicinity of the Russian Test Site at Novaya Zemlya. Overlapping red stars show the locations of past nuclear tests since 1977, including the last test on October 24, 1990. Seismic events from 1999 to 2009 with magnitude greater than 2.0 from the Norwegian organization NORSAR reviewed regional bulletin are shown as blue circles.[2] IMS primary stations (triangles), auxiliary station (squares) and some of the other publicly available stations (pentagons) are also shown. Some of the NORSAR events in Scandinavia (including Finland) and mainland Russia are associated with mine blasts. Overlapping orange diamonds locate seismic signals associated with the submarine Kursk disaster in 2000. Note that the area around the test site has a low level of some natural earthquake activity, as indicated by the blue circles. SOURCE: William Walter, Seismology Subcommittee member

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[2] See: *http://www.norsardata.no/NDC/bulletins/regional*.

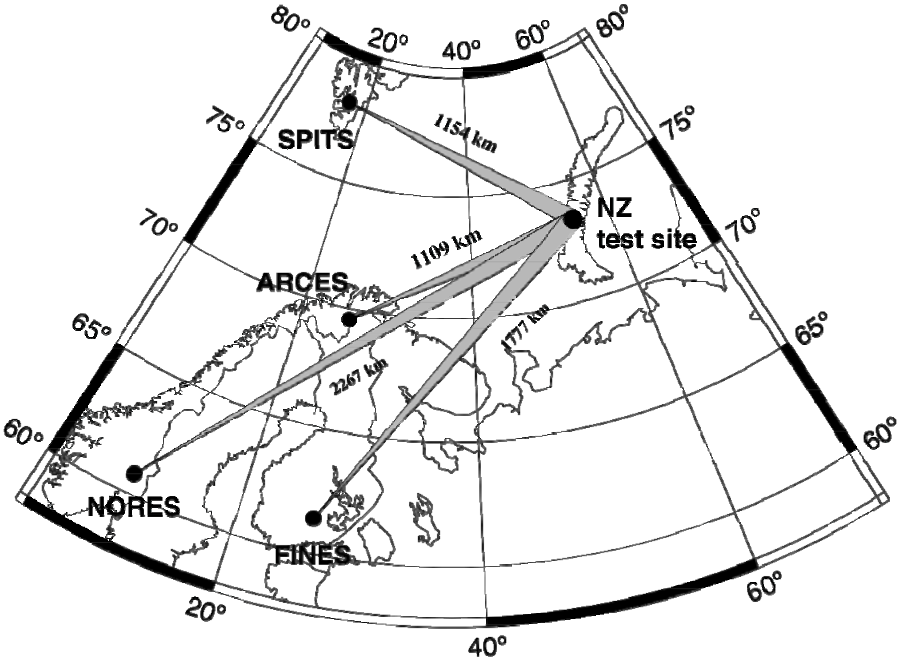

FIGURE D-3: Map of Novaya Zemlya and locations of four seismic arrays in Norway, Finland and Spitsbergen. SOURCE: Kværna et al., 2002

Seismologists at the Norwegian organization NORSAR have developed a program for monitoring the magnitude thresholds of specific sites on a continuous basis. It is particularly good for source areas of low earthquake activity as shown for Novaya Zemlya (Figure D-4) for a 24-hour period on February 9, 1998 (Kværna et al., 2002). Noise levels and spikes of energy received from earthquakes during that day (in the azimuthal beam focused on the test site at Novaya Zemlya) are indicated for each of the arrays in the bottom four panels and in the top panel for the network that consists of those four arrays. This is a “smart” network that for every possible event time at Novaya Zemlya favors the array(s) that have the least background energy at the corresponding (known) arrival delay for the explosion (P) waves. Magnitude thresholds at 90 percent confidence for detection on the vertical axes of each panel vary as a function of time and consist of background noise levels with superposed spikes of energy from earthquakes that are larger than background for brief time intervals. On the date in question the background noise is highest at NORES (approximately magnitude 2.9), and lowest at SPITS (magnitude 2.2). For the whole smart network (top panel), the background noise level for possible events at Novaya Zemlya is reduced to about magnitude 1.8. Because P waves from seismic events that are not at Novaya Zemlya arrive at different times, they are suppressed in the network trace. Hence, the number of spikes and their magnitudes are reduced for the network.

The largest excursions above background noise are associated with a distant earthquake (labeled 1) in the Sea of Okhotsk. On the network panel, that excursion reaches magnitude 3.1 but only for about 10 minutes. Hence, the threshold capability of the network as a detector of a realistic nuclear test on that day is about magnitude 1.8. Kværna et al. (2002) examined data for the last two months of 1997 and found a threshold capability most of the time at magnitude 2.0. For those two months and for all of 1998 they found some time periods in which those thresholds are as high as magnitude 2.5. The detection and identification thresholds for monitoring Novaya Zemlya are therefore estimated by the Seismology

Subcommittee to be in the range of magnitudes 2 to 2.5. Corresponding yields are discussed below.

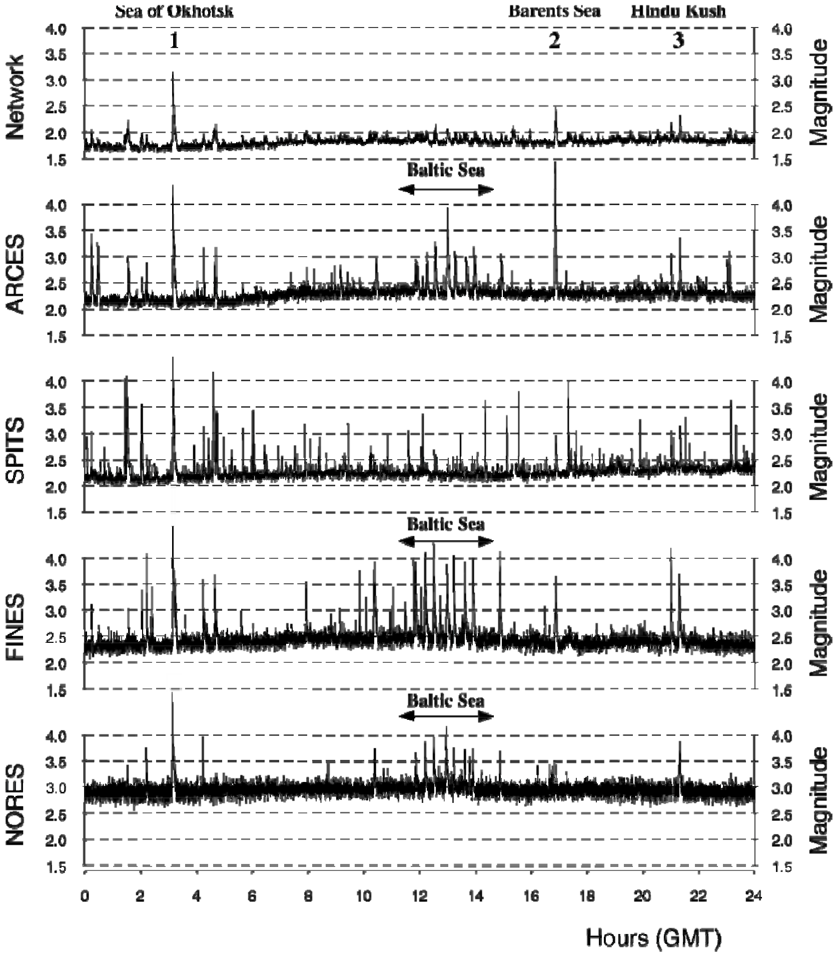

FIGURE D-4: Example of site-specific threshold ("smart network") monitoring for seismic events from Novaya Zemlya for 24 hours on February 9, 1998. SOURCE: Kværna et al., 2002

For well-coupled nuclear explosions at the main Russian test site at Novaya Zemlya, magnitude = 4.3 + B log Y (where Y is yield in kilotons)[3]. B is about 0.75 for explosions larger than 1 kt and results from larger explosions being detonated at increasingly greater depth to ensure containment. For very small nuclear explosions, the Seismology Subcommittee assumes that explosions would be at least as deep as previous 1 kt tests and hence take B = 1.0. It should be realized that at very small magnitudes, the calculation of yield is more uncertain because few calibration data exist for yields below 1 kt. Also, at low yields it can become practical to influence the environment of the nuclear device in ways that somewhat change its coupling to seismic energy, which can introduce additional uncertainty in yield estimates.

Hence, for magnitudes 2.0 and 2.5 one obtains Y = 5 to 15 tons (0.005 to 0.015 kt) if an underground explosion is fully coupled. For a decoupling factor (DF) of 40, Y = 200 to 630 tons. Assuming a potential evader is more conservative and uses a DF = 20 for hard rock in his assessment of yield associated with the detection limits at Novaya Zemlya, Y = 100 to 320 tons.

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[3] This magnitude-yield relation uses that of Murphy (1996) for hard rock at eastern Kazakhstan minus 0.15.

These yields for either fully coupled or fully decoupled nuclear tests are a fraction of a kiloton. See Appendix E for a discussion of decoupling factors in hard rock versus salt.

It should be realized that the above are 90 percent confidence limits for detection. From the viewpoint of a potential evader not wanting to be detected, a lower detection confidence level likely would be appropriate. For instance, a 10-percent probability of detection could result in the above yields for fully coupled and decoupled cases being reduced by a factor of about 2.5. In that case, for a risk-averse evader determined to conduct nuclear explosion a maximum yield for fully decoupled tests using a DF of 20-40 would be between 0.04 and 0.42 kilotons.

Because salt is not present in any appreciable thicknesses at Novaya Zemlya, decoupled tests would have to be conducted in hard rock. Somewhat smaller threshold yields than those above are obtained for the old Krasino test site in southern Novaya Zemlya where magnitude = 4.45 + B log Y, a relationship that also is appropriate for past tests at eastern Kazakhstan (Murphy, 1996), at Lop Nor, China, and in northern India.

Several small earthquakes have been detected, located, and identified in the vicinity of the Novaya Zemlya test site during the last 25 years. The 90 percent confidence limit for location of one of these, a magnitude 2.7 earthquake in 1992, included the test site. This event, events in the Kara Sea in 1986 and 1997, and two on the north island of Novaya Zemlya in 1995 and 1996 were claimed in the media to be either Russian nuclear tests or possible tests. Subsequent special studies showed that each of these was an earthquake (see Sykes, 1997).

The Kara Sea seismic event (magnitude about 3.5) of August 16, 1997, received the greatest amount of attention in the U.S. media. It was described soon after as having explosive characteristics (Gertz, 1997). The results of initial efforts to evaluate the location of the event were poor, but analysis of data from stations in mainland Norway, Finland and Spitsbergen quickly showed that it occurred in the Kara Sea, well to the southeast of the test site. Further work later confirmed that the event was a small earthquake.

The Seismology Subcommittee drew three lessons from the handling of the 1997 event 1) use all available data for accurate location estimates and event characterization 2) avoid the use of just a narrow range of azimuths such as those to southern Norway and Finland, and 3) provide a mechanism for new information to be updated to policy makers as it becomes available for occasional “problem” events of this type. For example, scientists at the UK Atomic Weapons Establishment who work on nuclear verification regularly publish papers about once a year in leading scientific journals about “problem” seismic events such as those in the Kara Sea in 1986 and 1997. Their thorough analyses have convinced nearly all seismologists that those events were earthquakes. In general, the occasional problem events that have arisen have—through the research they have motivated—resulted in significant improvements in operational monitoring.

Seismic waves from two explosions of local seismic magnitude 1.5 and 3.5 that led to the sinking of the Russian Kursk submarine in the Barents Sea on August 12, 2000 (Figure D-2) are described by Ringdal et al. (2000). The larger explosion was well recorded at stations in northern Europe and as far away as Kazakhstan. Subsequent depth charges set off by the Russian navy were recorded by the seismic array ARCES in northern Norway—another indication of how well the Barents Sea and Novaya Zemlya can be monitored.

Explosions in and around Novaya Zemlya can be identified by the usual seismic techniques, including high-frequency P-wave-to-S-wave amplitude ratios (e.g., Richards and Kim, 1997; Hartse, 1998). An example of typical differences is shown in Figure D-5 where the high frequency seismograms of the nuclear test have larger P-waves and smaller S-waves than do nearby earthquakes. By correcting for distance effects, we can compare P/S ratios for many events around Novaya Zemlya, as shown in Figure D-5. Note the 1997 Kara Sea event separates cleanly from the nuclear tests, as do more recent earthquakes in 2007 and 2009. The magnitude 2.8 (NORSAR ML) June 26, 2007 earthquake was located by NORSAR to within 50 km (31 mi) of prior nuclear tests. By combining these single-station results with similar measurements at other stations and with other discriminant measures, a very high degree of confidence in identifying small explosions in this region has been achieved. An earthquake of magnitude 4.5 (according to NORSAR) occurred close to the northern main island of Novaya Zemlya on October 11, 2010, as this report was being finalized. It was detected by many IMS stations and will be useful in calibrating teleseismic and regional travel times for the vicinity of the Russian test site.

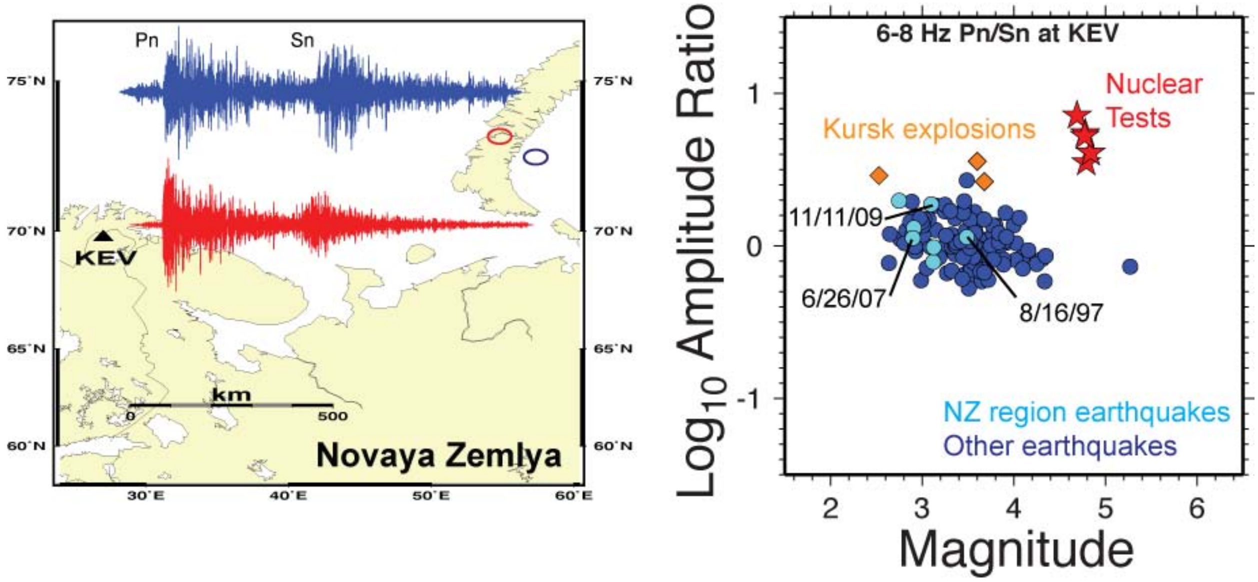

FIGURE D-5: Example showing how ratios of high frequency P-wave to S-wave amplitudes discriminate Novaya Zemlya nuclear tests from earthquakes. The left-hand side compares 6-8 Hz seismograms of the 1997 Kara Sea earthquake (blue) with the last nuclear test in 1990 (red). The right-hand side shows MDAC distance-corrected P/S values for five nuclear tests (red stars), Kursk related explosions in the water (orange diamonds), earthquakes around Novaya Zemlya (light blue circles) and other earthquakes around the Barents Sea (dark blue circles). The 1997 Kara Sea and more recent earthquakes in 2007 and 2009 are called out.
SOURCE: William Walter, Seismology Subcommittee member

In summary, the use of high-frequency seismic waves has come of age in the last 10 years as a valuable discriminant for earthquakes and underground explosions. The Russian test site at Novaya Zemlya is one of the world's best-monitored places of high concern to the United States. At 90 percent confidence, seismic events can be detected there down to magnitudes in the range of 2.0 to 2.5 corresponding to fully coupled explosions of about 5 to 15 tons (0.005 to 0.015 kilotons). As salt is not present on Novaya Zemlya in any appreciable thicknesses, any decoupled testing would have to be done in hard rock for which maximum decoupling factors of 20 to 40 are most appropriate. For decoupled explosions, detection at high confidence therefore corresponds to yields of about 100 to 600 tons. From the viewpoint of a potential evader not wanting to be detected, maximum decoupled yields of about 40 to 250 tons (0.04 to 0.25 kilotons) may be more appropriate. The low level of earthquake activity on and near Novaya Zemlya also makes monitoring the Russian test site easier.

Monitoring the Chinese Test Site at Lop Nor

China conducted all of its nuclear tests near Lop Nor in the sparsely populated northwestern part of the country. China stopped testing in 1996 just prior to signing the CTBT.

As a consequence, newer stations of the International Monitoring System (IMS) and other modern stations recorded more Chinese explosions in the 1990s than they did for other countries that stopped testing earlier. The Lop Nor area is seismically active when compared with the former Soviet Union's test site in eastern Kazakhstan (KTS) or the Russian test site on Novaya Zemlya, with several earthquakes of magnitude 4 and greater having occurred near the testing area over the past few decades. In this section we describe several techniques for distinguishing (discriminating) seismic waves of nuclear explosions from those of earthquakes since they are well illustrated for this test site.

Lop Nor is well monitored by arrays and seismic stations in Kazakhstan, Kyrgyzstan, Mongolia, Russia, Afghanistan, Pakistan, and Thailand. Eleven modern digital seismic stations in China are operated in conjunction with the U. S. Geological Survey. Most of these stations send data with a short time delay (within 30 minutes) to the IRIS data center in the United States and are openly available. The Chinese station Urumqi (assigned the station code WMQ by seismologists) is about 250 km (156 mi) from Lop Nor, closer than any other open station. Waveforms from WMQ are archived at IRIS on about a one-month delay. WMQ recorded a number of nuclear tests from eastern Kazakhstan before the Soviet Union halted testing there in 1989. IRIS archives also include a WMQ recording of one Lop Nor test, in 1988. Many other seismic stations at greater distances also recorded past Chinese nuclear explosions. Lop Nor is located near the southeastern side of the Tien Shan, a region of moderate earthquake activity and contemporary horizontal compressive stress in the earth's crust, which proves to be of significance in the discrimination of earthquakes from nuclear explosions in that region.

Sykes and Nettles (2009) found that more than half of the total numbers of earthquakes in the Reviewed Event Bulletin (REB) of the IMS that occurred within 100 km (62 mi) of six test sites from 2000 through 2008 occurred near Lop Nor. All seismic events near Lop Nor down to magnitude 3.4, the smallest event reported in the REB, were identified as earthquakes (Figure D-6), based on the ratio of P to Lg waves at frequencies from 4 to 16 Hz (Kim et al., 2009).

This high-frequency discriminant, which utilizes data from seismic stations around Lop Nor at regional distances, is one of the most important recent advances in nuclear verification. Hartse et al. (1997) published a regional discrimination study using earthquakes from northwest China and nuclear explosions from Lop Nor and KTS, demonstrating the effectiveness of the P/S ratio for frequencies at 3 Hz and greater. A method for improving regional discrimination performance was first applied to the Hartse el al. (1997) data set by Taylor and Hartse (1998). This magnitude and distance amplitude correction procedure (MDAC) was further refined by Taylor et al. (2002) and Walter and Taylor (2001) and is now routinely used for regional discrimination processing. Figure D-7 shows discrimination plots with MDAC corrections applied to earthquakes in the Lop Nor area and four nuclear explosions recorded at station MAKZ (780 km, or 488 mi) northwest of Lop Nor in eastern Kazakhstan.

Determining accurate depths is important in identifying many seismic events as earthquakes. This can be done using the time delay between the first-arriving P waves and slightly later waves that reflect off the surface of the earth, which are commonly called "depth phases." Seismic arrays provide a powerful tool for identifying depth phases, especially for events smaller than about magnitude 4.5.

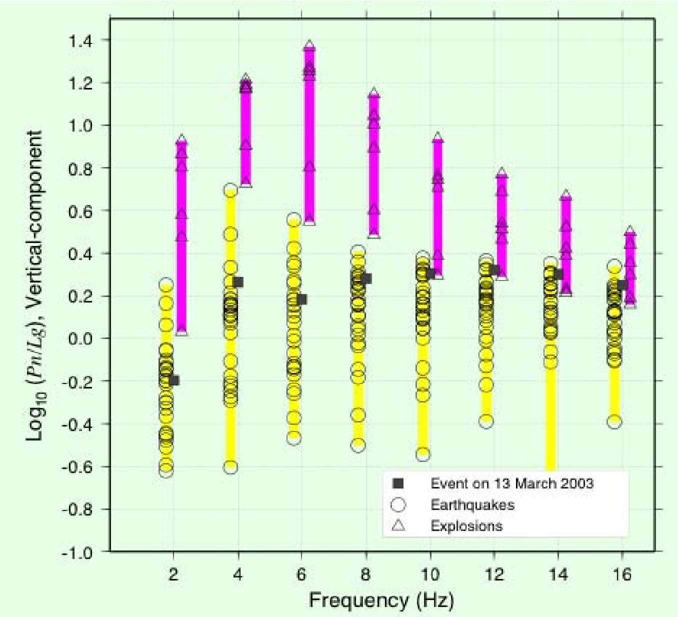

FIGURE D-6: Measurements of amplitude ratio P to Lg waves as a function of frequency for seismic events within 100 km (62 mi) of Lop Nor test site. Known nuclear explosions (triangles, with full amplitude range marked in pink) consistently have higher values than most earthquakes (circles, with full range in yellow). Figure D-6 includes 27 earthquakes of magnitude greater than 3.4, and 6 underground nuclear explosions. SOURCE: Kim et al., 2009 (reproduced with permission of the American Geophysical Union)

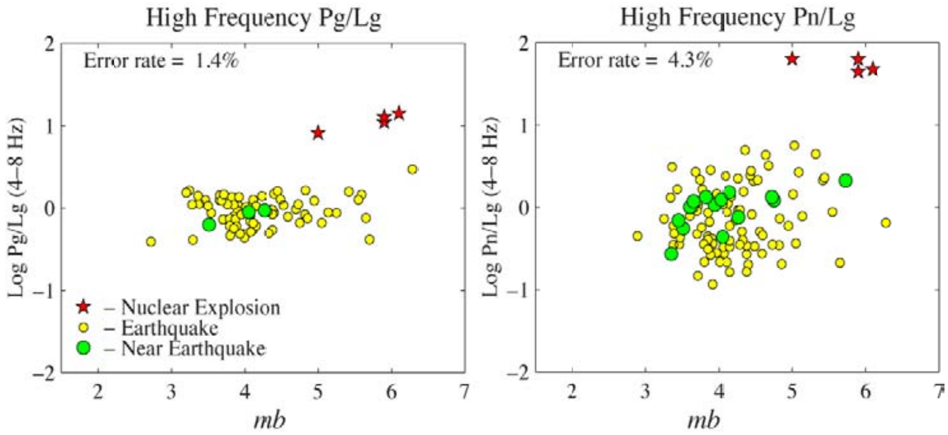

FIGURE D-7: High frequency Pg/Lg and Pn/Lg discrimination plots after application of the MDAC procedure. Stars are Lop Nor nuclear explosions from the 1990s recorded at station MAKZ in Kazakhstan. Green circles are earthquakes from within 100 km (62 miles) of the test site, and yellow circles are earthquakes from other regions of northwestern China. The “error rate” is the least-squares probability of misclassification with a discriminant line midway between the two populations. SOURCE: Modified from Hartse, 2000

Centroid Moment Tensor (CMT) solutions, which utilize the entire long-period seismogram, enable an analyst to determine if an event is an earthquake, explosion, or mine collapse and to estimate its depth. During the last 10 years, CMT solutions for the entire world have been extended downward from about magnitude 5.6 to 5.0 and are available over the

Internet within a few hours. This technique has been utilized for seismic events as low as magnitudes 3.3 for the Nevada Test Site and as small as 4.0 for those near Lop Nor (Sykes and Nettles, 2009).

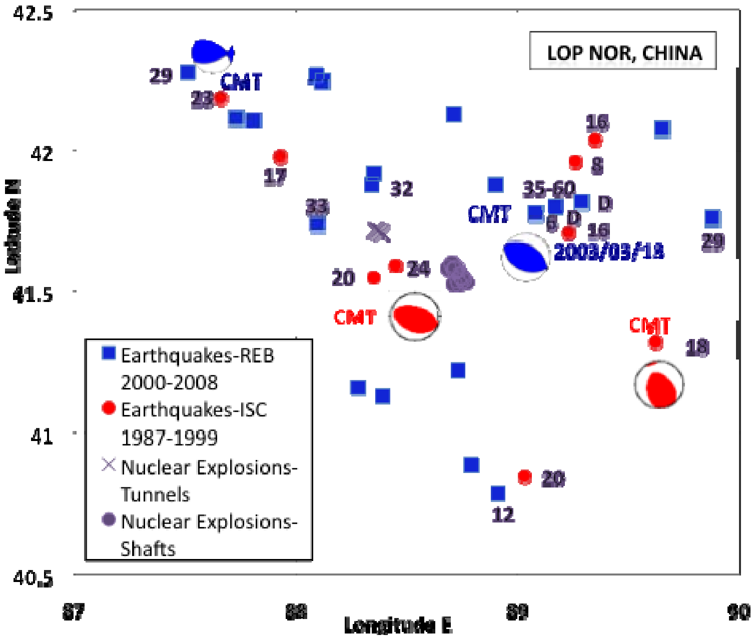

FIGURE D-8: Seismic events identified as earthquakes within 100 km (62 miles) of the Lop Nor test site in northwestern China as reported in Reviewed Event Bulletins (REB) of the CTBTO from 2000 through 2008. Red circles denote locations of selected large earthquakes from 1987 through 1999 from International Seismological Centre (ISC). Sites of tunnels and shafts used for nuclear tests from Waldhauser et al. (2004). Four "beach balls" in color indicate focal mechanisms (CMTs). Black numerals beside earthquakes denote their depths in km.
SOURCE: Adapted from Sykes and Nettles, 2009

Figure D-8 shows seismic events located near the Lop Nor test site in the Reviewed Event Bulletin of the CTBTO IDC in Vienna. The four CMT solutions, shown as colored "beach balls," indicate that those events were earthquakes. Each of the four is characterized by a large component of horizontal compression, as is found farther northwest along the Tien Shan in China and central Asia. In contrast, no seismic activity was located in the triangular southwestern one-third of Figure D-8 within the old and rigid crust of the Tarim basin.

All of the well-determined depths of earthquakes (numerals in Figure D-8) are between 5 and 35-60 km (between 3 and 22-38 mi), much deeper than past underground nuclear explosions at either Lop Nor or other test sites. Hence, at Lop Nor, the determination of depth is an important seismic discriminant. Most earthquakes within 100 km (62 mi) of the Nevada Test Site are shallower. They are identified better with the CMT methodology than with depth phases.

Figure D-8 also shows the locations of past underground nuclear explosions at Lop Nor. Their locations are very well known and are concentrated in two small areas.

Sykes and Nettles (2009) examined additional seismic discriminants for events near Lop Nor. Clear downward first motion of P waves at the Urumqi station for 7 of 20 events indicates that those 7, in fact, were earthquakes. Earthquakes generate downward motion at some take-off angles from their sources and upward first motion from others. (The colored and white parts of the four "beach balls" in Figure D-8 denote upward and downward first motions.) In contrast, an explosion produces only upward (compressional) first motion at all stations (a "beach ball" that would be one solid color). First motion was proposed in the late 1950s as an important discriminant between earthquakes and explosions but was found to be not very useful when data were available only at great (teleseismic) distances from an event. For example, distant stations typically record only upward first motions from earthquakes near Lop Nor; hence, those signals alone do *not* classify a seismic event near Lop Nor as either an earthquake or an explosion. The availability of data from closer regional stations, however, permits different take-off angles to be sampled. The types of "beach balls" in Figure D-8, which result from strong horizontal compression in the earth's crust, indicate that downward P wave motion should be observed at some regional stations, which it is. Clear downward first motion of several P waves is another instance in which data from regional stations in Asia are invaluable for identifying seismic events as earthquakes, not explosions.

A seismic event near Lop Nor of magnitude 4.3 on March 13, 2003, was recognized as difficult to identify using teleseismic methods. Special studies of this "problem event" indicate that it was, in fact, an earthquake. Five distinct techniques (Selby et al., 2005; Sykes and Nettles, 2009) confirm this (1) its high-frequency P-to-Lg ratio (Figure D-7), (2) downward first motion of the Pg wave at Urumqi, (3) depth phases, (4) its CMT mechanism, and (5) some determinations of M_s-m_b. Because earthquakes will occur in the future, there will be an ongoing need to make special studies of the occasional "problem event" like this and to update policy makers as more definitive results become available.

Detection Capability and Yield Estimation

A number of studies have examined the detection and location of small events near Lop Nor. Hartse et al. (1998) examined earthquakes in western China as small as magnitude 2.5. Hartse found that the catalogs of the Chinese State Seismological Bureau from 1973 to 1989 were complete to near magnitude 2.5. Other studies using the Makanchi station and its nearby array in eastern Kazakhstan, the closest seismic monitoring of Lop Nor outside of China, had a detection capability down to magnitude 2.8. Each of those studies is more than 10 years old, and the capabilities are likely better today. The Kazakhstan National Data Centre has a web-published bulletin that reports small events within a few hundred kilometers of Lop Nor.

An appropriate formula for explosions at Lop Nor that are smaller than one kiloton is magnitude = 4.45 + log (Yield in kt). That formula is appropriate to hard rock and good transmission of P waves to distant stations and applies also to southern Novaya Zemlya, the Indian test site, and Azgir, Kazakhstan. It was derived originally for eastern Kazakhstan (see Ringdal et al., 1992; Murphy, 1996). Magnitude 2.8 translates into a yield of 0.02 kilotons (20 tons) fully coupled in hard rock. For decoupling factors of 20 and 40, the corresponding yields are 0.4 and 0.9 kt, respectively.

Summary

Seismic monitoring of the Chinese test site at Lop Nor during the past decade has improved greatly with the availability of data from stations and seismic arrays in many surrounding and nearby countries. This has permitted smaller events to be located and high-frequency techniques to be used for identification of an event as being either an earthquake or an underground explosion. Since nuclear-explosion testing stopped in 1996, many seismic events near Lop Nor can be identified as earthquakes from a variety of other discrimination techniques including depth, first-motion of P waves, regional CMT focal mechanism, and the difference in amplitudes of long-period surface waves and short-period P-waves (M_s-m_b).

Unclassified information indicates that events of magnitude 2.8 and larger can be detected. This translates into a yield of about 20 tons fully coupled in hard rock. For decoupling factors of 20 and 40, the yield is about 0.4 and 0.9 kt.

Monitoring North Korea

North Korea has not signed the CTBT. North Korea originally signed the Nuclear Non-Proliferation Treaty (NPT) and ratified it in 1985. However following a number of indications and accusations that North Korea was not abiding by the NPT, North Korea withdrew from the NPT in 2003. In 2005, North Korea declared that it possessed nuclear weapons.

On October 9, 2006, North Korea announced that it had conducted a nuclear test. Seismic signals from the event registered magnitude 4.1 (IDC-REB), and radionuclides from the test were detected. On October 16, 2006, the U.S. National Director of Intelligence released a statement: "Analysis of air samples collected on October 11, 2006 detected radioactive debris which confirms that North Korea conducted an underground nuclear explosion in the vicinity of P'unggye on October 9, 2006. The explosion yield was less than a kiloton" (DNI news release, 2006).

On May 25, 2009, North Korea declared it had conducted a second nuclear test. Seismic signals registered a magnitude 4.5 (IDC-REB), but radionuclides were not detected. On June 15th, the U.S. Director of National Intelligence released a statement that "North Korea probably conducted an underground nuclear test…(t)he explosion yield was approximately a few kilotons" (DNI news release, 2009).

The number of natural earthquakes per year in North Korea is lower than in some of the surrounding regions of China, Japan, and South Korea, as shown in Figure D-9. On average, North Korea has a natural earthquake over magnitude 4 only once every few years, so the nuclear tests stood out as unusual, just because of their location and size. There are several IMS primary and auxiliary seismic stations within 1,200 km (750 mi) of North Korea. Within the same distance, additional seismic stations, which are also shown in Figure D-9, are publicly available and were used by seismic researchers to analyze the tests in the days immediately afterward. Because of their concerns about earthquake hazards, China, Japan, and South Korea each maintain additional dense networks of seismic stations not shown in Figure D-9. Although these stations are not all publicly available, researchers in these countries have used them in analysis of the North Korean tests (e.g., Hong et al., 2008).

Earthquakes in this region are routinely reported in local and global catalogs at levels of magnitude 3 and below. There are also mine blasts and industrial chemical explosions in the region, but these are usually smaller than magnitude 3.5. Mine blasts and other non-earthquake seismic events are mostly excluded from the seismic catalogs by design, as the principal use of the catalogs is for earthquake hazard.

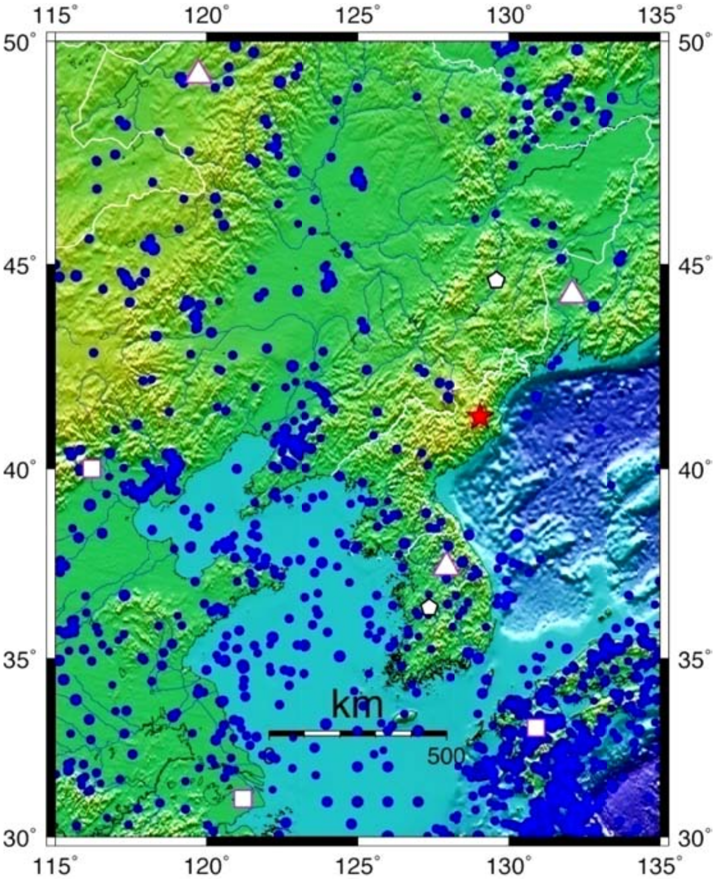

FIGURE D-9: Map showing the location of seismic events (blue dots) and stations in the vicinity of North Korea. The seismic locations of the 2006 and 2009 North Korean declared nuclear tests are shown by overlapping red stars. Other crustal (depth < 35 km, or 22 mi) seismic events from 1999 to 2009 with magnitude > 3 from several catalogs (REB, NEIC, ISC and the Korean Institute of Geosciences and Mineral Resources [KIGAM]) are shown as blue circles. IMS primary stations (triangles), auxiliary stations (squares) and some of the other publicly available stations (pentagons) are shown in white. SOURCE: William Walter, Seismology Subcommittee member

A number of researchers noted that 2009 nuclear test seismic waveforms look very similar to seismic waveforms from the 2006 event if that test is scaled up by a factor of around 4-6 (e.g., CTBTO Press Centre, 2009; Ford et al., 2009). This similarity between waveforms has been used by a number of different research groups to get very accurate relative locations between the events, and the best indications are that the two tests were located within about two-and-a-half kilometers of one another (e.g., Wen and Long, 2010). The absolute location of the two tests is less precisely known, but because the 2009 test was recorded by a large number of stations the IMS estimate of location error is relatively small: the 90 percent confidence region is roughly circular and about 10 km (6.2 mi) in diameter (CTBTO Press Centre, 2009).

The seismic signals from the two tests clearly indicated they were explosions and not earthquakes. Primarily this was shown by the regional high frequency P/S ratios from the 2006 test (e.g., Kim and Richards, 2007; Richards and Kim, 2007; Walter et al., 2007) and by moment tensor analysis (e.g., Ford et al., 2009). The 2006 nuclear explosion was an excellent real-world test of empirical seismic methods for a sub-kiloton explosion in a new region, and the discrimination methods worked very well as shown in Figure D-10. Because the 2009 test had such similar seismic signals to the 2006 test, the discrimination results for the two tests are very similar. One important difference is that the 2009 test generated a very small infrasound signal (e.g., Che et al., 2009). The small size of the infrasound signal compared with the seismic signal can be used to determine that this event was not a surface explosion, such as those that might occur in an open pit mine, although this event was much larger than the usual mine-related blasts.

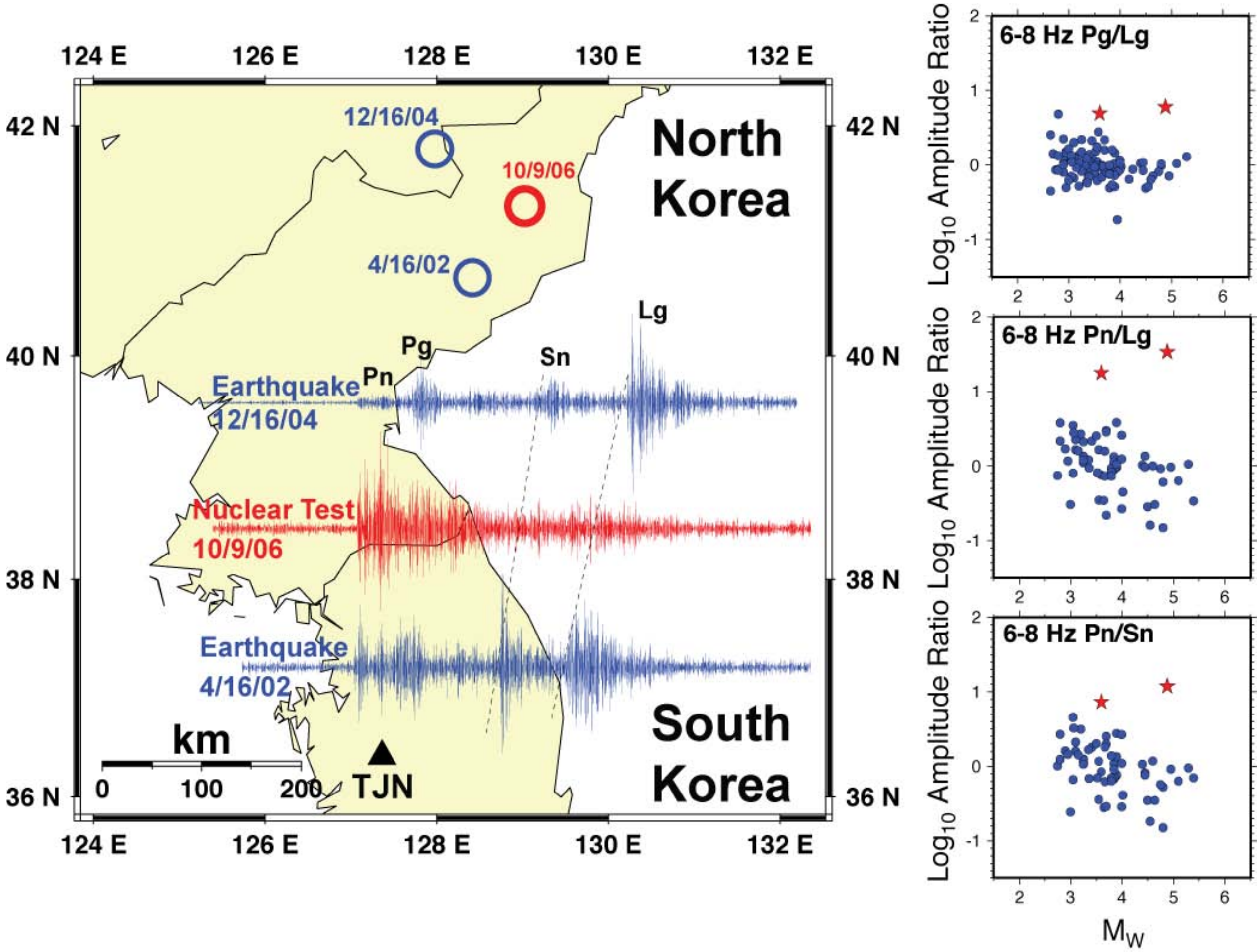

FIGURE D-10: Example showing how ratios of P-wave to S-wave amplitudes discriminate the 2006 and 2009 nuclear tests in North Korea (red seismogram represents data from the 2006 test, and stars on the right indicate 2006 and 2009 test data) from earthquakes in the region (blue seismograms and symbols). At distances of a few hundred kilometers the Earth separates P-waves into two groups, a mantle path (Pn) and crustal path (Pg). S-waves are similarly separated into Sn and Lg. As expected, the 2006 explosion shows stronger P-waves and weaker S-waves than do nearby earthquakes. When we measure these P/S amplitudes at high frequencies (e.g., 6-8 Hz here) and correct for path effects, we get the plots shown on the right (stations TJN and MDJ averaged), showing that the explosions stand out from the earthquakes. Seismologists can statistically combine such measures to achieve excellent explosion identification capability down to very low magnitude in this region. SOURCE: Adapted from Walter et al., 2007

An unclassified discussion of the various techniques to detect, locate, and identify nuclear tests is given in Chapter 2. Interestingly, although there is separation between the North Korean tests and nearby earthquakes when using the older Ms-mb earthquake-explosion discrimination method (e.g., Bonner et al., 2008; Bowers and Selby, 2009), the separation is not as good as previous tests. This may be related to depth of burial or other emplacement conditions, which have not been released by the North Koreans. Because of this lack of information about the emplacement conditions, uncertainty also remains concerning the yields of the two tests, although (as is apparent from the DNI statements) they can be estimated approximately as less than a kiloton for the 2006 test and a few kilotons for the 2009 test. The relative location of the two tests, and the ratio of their yields, can be determined more accurately than their absolute locations and absolute yields (e.g., Kim et al., 2009).

A topic of much discussion for the 2006 and 2009 North Korean tests is why 2006 had detectable radionuclides and 2009 did not. Containment of radionuclides following a test is complex, but it is thought that it may be harder for a smaller test than for a larger one, because for the larger test it may be more straightforward to establish a “stress containment cage” that prevents the formation of cracks through which radionuclides escape to the atmosphere. An underground nuclear explosion creates a cavity that shrinks slightly from its maximum size. In this shrinking process, compressive stresses are generated that act to close down cracks—by which (if they stayed open) radionuclides would have opportunities to escape to the atmosphere. The shrinking back from the maximum helps to provide containment (OTA Report, 1989, pp. 34-35, 48).

One result the two North Korean tests made very clear is that if multiple nuclear tests occur in the same region, then relative methods of detection, location, discrimination, and yield estimation can be brought to bear on the verification problem. These relative techniques often are more precise than absolute methods, and they provide additional confidence that the verification task is made easier in a region with multiple tests.

Monitoring the Middle East, Iran and South Asia

Several countries in the Middle East and North Africa have or are considering nuclear reactors for research and/or nuclear energy generation. A subset of these countries is listed in the CTBT Annex 2; as such, they must ratify the CTBT before it can enter into force. Information on some of these countries is given in the Table D-1.

There are no declared possessors of nuclear weapons in the Middle East region. However, there are ongoing concerns over activities in Iran and Syria, and Israel maintains a policy of nuclear ambiguity. Given the expanding commercial nuclear energy facilities in the region and longstanding non-proliferation concerns, the Middle East is a major area of concern for CTBT monitoring.

TABLE D-1: Partial list of Commercial Nuclear Reactor Plans for the Middle East and North Africa.

Country	Nuclear Reactor Plans	CTBT Annex 2 States?
Algeria	Plans for first commercial reactor around 2020 (two research reactors, 1989 and 1993)	Yes
Egypt	Announced plan in 2007 to build several reactors (two research reactors, 1958 and 1998)	Yes
Israel	No definite commercial plans (two research reactors, 1960 and 1962)	Yes
Iran	First commercial plant fueled in 2010 (several research reactors since 1967)	Yes
Jordan	Plans to build a nuclear power plant by 2017	No
Kuwait	Considering developing nuclear power	No
Libya	In talks with Russia to build a plant (research reactor)	No
Qatar	Agreement with France for cooperation	No
Saudi Arabia	In talks with France to develop nuclear power	No
Syria	Expressed interest in 2007 (small research reactor)	No
Turkey	Discussions of seeking bids for four new plants (three research reactors)	Yes
UAE	South Korea consortium to build 4 plants 2017–2020	No

*SOURCE: Adapted from Fineren et al., 2009; NRC, 2009; Nuclear Threat Initiative Research Library, 2010; U.S. Department of State, 1997; and World Nuclear Association, 2009.

There have been no nuclear tests in the broad Middle East region running from Egypt and Turkey in the West to Iran in the East. However, Pakistan and India, just to the east of this region, in Southwest Asia, both tested nuclear devices in 1998 (see Figure D-11). The number of natural earthquakes in this region is quite high, as shown in Figure D-11. Compared with the North Korean region shown in Figure D-9, the broad Middle East and Southwest Asia region shown below has about twenty times as many earthquakes per year. Whereas North Korea has a magnitude 4 earthquake only every few years, Iran has a magnitude 4 earthquake on average once a week. In practice, the earthquakes occur more in concentrated main-shock and aftershock sequences than constantly over time, but the overall burden to identify these seismic events as earthquakes, and not of concern under the CTBT, is significant in this region. On the other hand, the large number of natural events provides a considerable amount of data for use in calibrating this region.

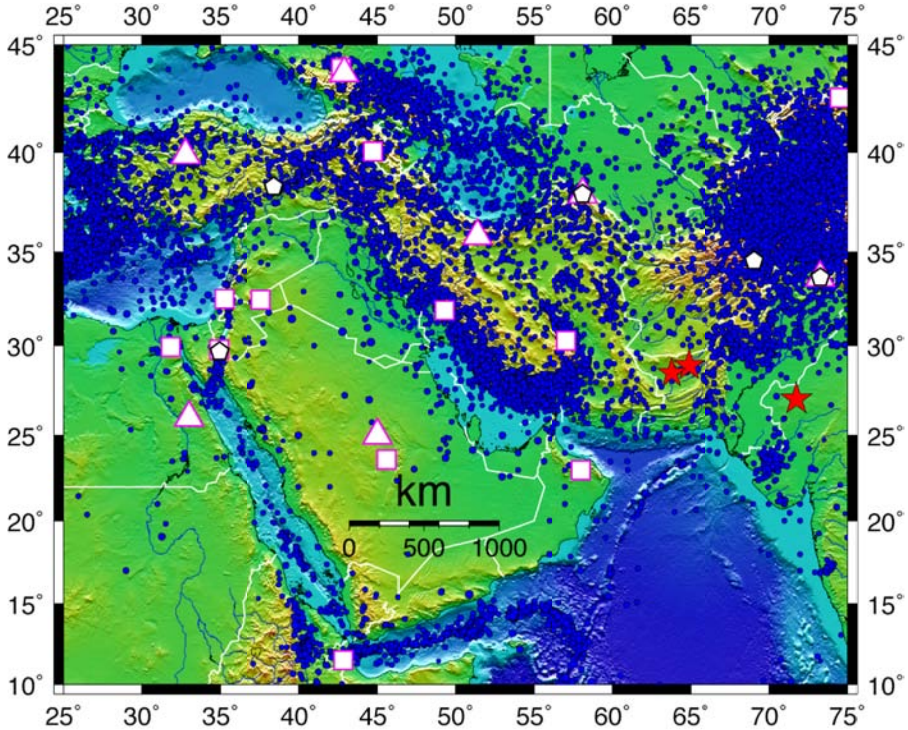

FIGURE D-11: Map showing the location of seismic events and stations in the broad Middle East and Southwest Asia region. The seismic locations of the 1998 Indian and Pakistan declared nuclear tests are shown by red stars. Other crustal (depth < 35 km or 22 mi) seismic events from 1999-2009 with magnitude > 3.5 from several catalogs (REB, NEIC, ISC, KOERI, IRSC) are shown as blue circles. IMS primary stations (triangles), auxiliary stations (squares), and some of the other publicly available stations (pentagons) are shown in white.
SOURCE: William Walter, Seismology Subcommittee member

The large number of earthquakes reflects the active tectonics of this region. The Indian, Arabian, and African tectonic plates are all being driven northward into Eurasia, pushing up mountains and causing large earthquakes. The significant earthquake hazard in this region has led many countries to install large numbers (hundreds) of seismic stations to monitor and study the situation. Turkey, Israel, Saudi Arabia, Azerbaijan, and Iran, among others, maintain dense seismic networks and although only some of these data are available via publically accessible websites, they are not restricted and can often be acquired by scientists who know how to request them. There are a number of existing and planned IMS stations in the region shown in Figure D-11. Several, however, have not yet been built (e.g., Egypt, Saudi Arabia), and ones in Iran that have been built and certified by the IMS are not sending data. Iran’s stated position is that it will not send data until entry into force (EIF) of the CTBT. Pakistan and India have not signed the CTBT and are not actively participating in the work of the CTBTO at this time.

The active tectonics and alterations of the earth’s crust and upper mantle complicate the propagation of seismic waves in this region. The geological activity is associated with the rapid attenuation of seismic signals for some paths, raising detection thresholds. The structural complications also degrade the location accuracy of seismic events and explosion identification unless they are accounted for. For these reasons, the Middle East has been the focus of much seismic research and development effort aimed at using the large number of earthquakes to calibrate the region.

Seismic location can be improved by taking advantage of past earthquakes that have very good location accuracy based on a local network, which may have been temporarily deployed after a large event. Seismologists have defined criteria for how well these reference events (also called "ground truth" events) are located (e.g., Bondar et al., 2004). When good ground truth reference events are available, statistical techniques such as "kriging" can be used to locate nearby events very accurately (e.g., Schultz et al., 1998). For example, reference events have been used to develop source-specific station corrections (SSSCs) that account for the variation in Earth structure and improve location accuracy (e.g., Richards et al., 2003).

To cover broad areas where such ground truth reference events might not be available, tomographic methods are used. As in medical tomography where x-rays are used to image inside the human body, seismic waves are used to image inside the earth. As seismic waves travel through complex geology their speed and amplitude are altered. By examining many paths crossing through a region one can quantify these variations and correct for their effects on observed signals, for purposes of using these waveforms to obtain improved information on the location and size of seismic sources.

A very large tomographic study of Eurasia using about 600,000 regional P-wave ("Pn" phase) paths to improve event locations has been completed by the national laboratories and USNDC staff (Myers et al., 2010). Based on tests using well-located reference events and regional Pn arrivals at four stations, this model improves the median location error from about 32 km (20 mi) using the best 1-D Earth model (ak135) to about 15 km (9 mi). Four stations are close to the minimum number needed for location and so this represents a small event near the monitoring limits. With additional station detections the location error can be reduced further. Through this model can be applied anywhere in Eurasia, it is particularly useful in a geologically complex region such as the Middle East and in places where more accurate SSSCs are not available.

Identification of explosions in the Middle East and Southwest Asia can be accomplished by the usual methods of Ms-mb, depth, moment tensor analysis, and regional high frequency P/S ratios. For example in Figure D-12, the May 11, 1998, Indian nuclear test (shown in red) is easily distinguished by its large P/S amplitude ratio compared to a nearby earthquake (shown in green) at station NIL (an IRIS GSN publicly available station), located very close to the planned primary IMS seismic station in Pakistan.

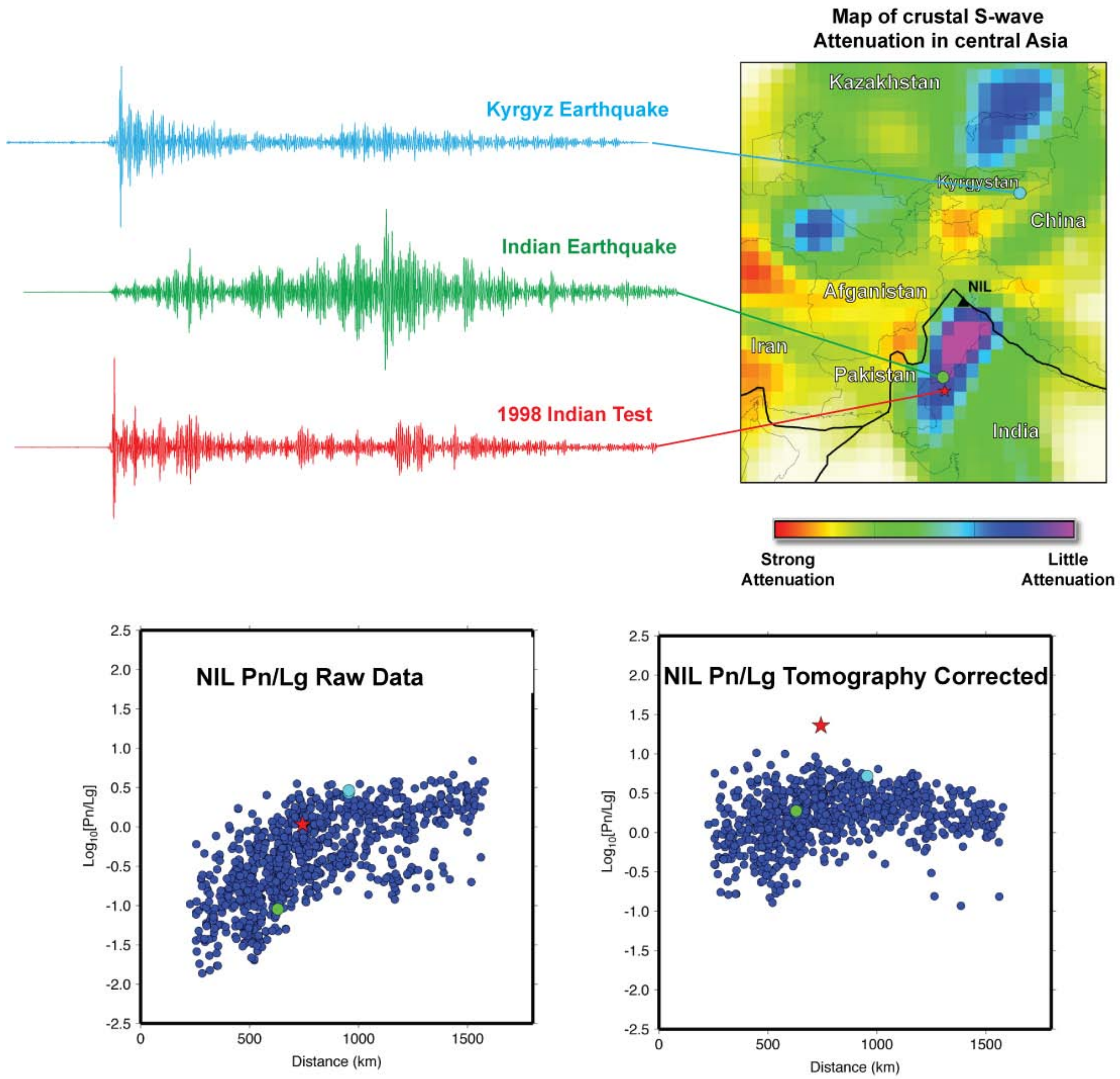

FIGURE D-12: The 1998 Indian nuclear test seismogram (red) compared with two earthquakes at station NIL in Pakistan. The nearby earthquake (green) shows the characteristic small P-waves at the beginning and large S-waves in the middle of the seismogram. These P/S differences are used to discriminate explosions from earthquakes. An earthquake in Kyrgyzstan to the north is filtered by the Earth as it travels to the station so that it ends up looking very similar to the explosion. By accounting for these path effects using amplitude tomography as shown in the upper right in terms of Qs (Pasyanos et al., 2009), these path effects can be removed. In the bottom plots, P/Lg ratios (Lg is a type of S-wave) for many earthquakes all over the region are compared and after correcting for the path effects, the explosion (red star) stands out and is discriminated from all the earthquakes (blue circles), including both the nearby Indian earthquake (green circle) and more distant Kyrgyz earthquake (light blue circle).
SOURCE: Adapted from Pasyanos and Walter, 2009

However, there may not always be a good reference earthquake with which to compare a new unknown event, and the complex Earth structure in some regions can make an earthquake seismogram look like an explosion. For example in Figure D-12 the Earth has filtered the seismogram of an Kyrgyz earthquake, shown in blue, at NIL in such a way as to resemble the 1998 explosion seismogram. By taking advantage of the many previous earthquakes recorded at the many tens of available seismic stations deployed for earthquake hazard purposes, we can map out these path effects and correct for them using tomographic methods. The result, as shown in Figure D-12, is the ability to quickly identify explosions using their individual regional seismic signals in a large and tectonically complex area, without the necessity of having a good nearby reference event in each case.

In addition to tomography, the amplitudes of nearby events can be used via methods such as kriging to predict the amplitude variations due to propagation, and such corrections have been used to improve P/S discriminations (see, e.g., Bottone et al., 2002). In practice, kriged corrections from past events can be combined with tomographic corrections to get even better corrections (see, e.g., Pasyanos, 2000). Such path corrections are important when identifying explosions and discriminating them from earthquakes in a complex region like the Middle East and southwest Asia.

Another way to take advantage of the large number of seismic events in the Middle East is to use waveform correlation. Tests in California and China have found that a very large number of the earthquakes correlate with each other (e.g. Schaff, 2009). In this methodology, the waveforms of all events are compared and clusters are created of very similar waveforms. It can be shown that seismic waveforms that match each other with a high degree of correlation must be located close to each other and have similar sources (see, e.g., Schaff, 2008). So once a new event is correlated with a well-characterized cluster, the event can be detected, located and identified through the correlation process. These correlation techniques are also particularly useful for detecting and identifying mine blasts (see, e.g., Harris, 1991).

APPENDIX E[1]

Dealing with Evasive Underground Nuclear Testing

Several schemes for clandestine testing have been proposed since 1959 when the concept of decoupling was first introduced (i.e., setting off nuclear explosions in large, deeply-buried underground chambers).

In the last 10 years, the deployment of sensitive seismographs and arrays—especially in a swath across China, Russia and other former (now independent) states of the Soviet Union, the Middle East, and other parts of Asia—provides an abundance of data that was not available previously to the United States. Access to seismic data at high frequencies and closer distances and for much smaller events makes the two most serious cheating scenarios—decoupled nuclear testing and mine masking—easier to detect and identify. This appendix describes the obstacles facing a country that wants to conduct a clandestine test in secret and yet not have one or several aspects detected by either the United States or other countries. It addresses whether decoupled testing can be done at yields of possible military significance by countries of special concern to the United States. Whereas detection capabilities have increased greatly during the last 10 years, relatively little is new in computer modeling of decoupling and in experiments with chemical explosives.

Decoupled Testing

If a nuclear explosion is detonated in a large cavity deep underground, the seismic waves generated can be reduced in amplitude. This method of evasion is called decoupling, and the amount of seismic-wave reduction is called the decoupling factor (DF). For a fully[2] decoupled nuclear explosion, most of the explosive energy goes into increasing the gas pressure in the cavity by as much as 100 times atmospheric pressure.[3] This is in contrast to a normal "well coupled" underground explosion where much of the energy goes into melting and deforming the surrounding rock and in generating larger seismic waves.

Although the concept of decoupling was proposed 50 years ago, data on decoupled nuclear explosions are very sparse and mostly 25 to 50 years old. This is surprising because decoupling as a cheating scenario has been mentioned repeatedly for 50 years as one of the main impediments to verifying a treaty that would ban underground testing. In the era of nuclear testing before September 1996, when the United States, Russia, the United Kingdom, France, and China signed the CTBT and began a moratorium, nuclear experiments by the United States to test this scenario were not considered important enough for them to be given priority and financial support except at very small yields.

A country wanting to conduct a clandestine explosion as large as 1 to 5 kilotons with a high probability that it would not be detected would have to meet all of the many criteria described below. The greater the amount of equipment deployed before, during, and after a

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[1] This appendix is drawn from the work of the Seismology Subcommittee (see Appendix A), which was directed by the main committee to investigate issues related to seismology and evasion.

[2] The word *fully* simply means that rocks subjected to explosive energy in a decoupled test are not stressed beyond their elastic limit. *Fully decoupled* does not mean seismic waves are reduced to zero amplitude. The decoupling factor is not increased by yet greater enlargement of the cavity.

[3] Computed for 1 kt explosion in a cavity in salt of radius of about 25 m at a depth of 1 km as scaled from data of the Sterling decoupled nuclear explosion (Denny and Goodman, 1990).

clandestine test, the greater the chance that it would be detected. This is even more true for a series of tests of a new nuclear device of military significance.[4]

Strong views exist today as they have for 50 years—both pro and con—of the feasibility of conducting a secret decoupled explosion of significant yield. In general, experts agree that seismic signals from an underground nuclear explosion can be reduced by a large amount but that the technique is impractical for yields above 10 kilotons (Turnbull, 2002). In this appendix, the Seismology Subcommittee argues that decoupled testing with yields of 1 to 10 kilotons with decoupling factors of 50 to 100 is not credible for countries of concern to the United States and that such tests likely would be detected with present monitoring capabilities.

The following sections discuss three decoupled nuclear explosions and what can be learned from them, cavities created by past nuclear explosions in salt that might be used for future clandestine testing, use of large cavities in thick salt deposits, and testing in mined cavities in hard rock. Salt is emphasized because cavities likely exist in that material from past nuclear explosions in the Former Soviet Union, and very large cavities at depth are easiest to construct in salt. Thick salt deposits at suitable depths for decoupled testing exist in some countries but not in others, such as North Korea. The feasibility of evasive testing is very much a function of the size or yield of an explosion a country wishes to test. Finally, this appendix lists the several significant obstacles a country would face in deciding to conduct a decoupled test and have a high likelihood that it would not be detected.

Known decoupled nuclear explosions

The database of decoupled nuclear explosions is very meager. It includes the only one that was nearly fully decoupled (Sterling), one partially decoupled (Azgir), and one small U.S. nuclear explosion that may have been decoupled significantly but by an unknown amount. They are the following:

- Sterling, a 0.38 kiloton (380 ton) nuclear explosion, was detonated in 1966 in the cavity generated by the 5.3 kiloton fully-coupled Salmon nuclear explosion in a salt dome in Mississippi. A decoupling factor of about 72 ± 8 was calculated. A factor of about 70 has occurred repeatedly since then in discussions about evasive testing. Assertions such as "This means a 70 kiloton test can be made to look like a 1-kiloton test, which the CTBT monitoring system will not be able to detect" is doubly false, in that a 70 kt explosion cannot be fully decoupled, and the IMS will confidently detect a signal produced by a 1 kt test. What Sterling showed, in fact, was that a 0.38-kiloton test could be decoupled by a factor of about 70. Detection and identification, which we address in this report, have improved immensely since 1966. Both decoupling and detection of larger decoupled explosions are discussed.
- In 1976, the Soviet Union conducted a partially decoupled nuclear explosion of 8 to 10 kilotons in a huge cavity of mean diameter of 243 feet (74 m) in a salt dome at Azgir, which is now in the Republic of Kazakhstan (Sykes, 1996; Sultanov et al., 1999; Murphy, 2009). That cavity had been created at a depth of nearly 3,000 feet (1,000 meters) by a well-coupled nuclear explosion in 1971 with a yield of 64 kilotons (magnitude 6.06). Even in 1976—prior to the subsequent increase in deployed seismic instruments—that event was well recorded by many stations in Europe and Asia and as far away as Canada with

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[4] This appendix emphasizes decoupling factors larger than 3, since reduction in seismic amplitudes at about this level can be obtained by testing in regions where either seismic waves propagate less efficiently, explosions are detonated at greater depths than past nuclear weapons tests or in weak rock geologies.

magnitude 4.06 (Sykes, 1996). It was decoupled by a factor (DF) of 12 to 15 times.[5] According to news reports at the time, it was promptly identified as originating from a decoupled nuclear test. Because the yield of the 1976 explosion was more than 20 times that of Sterling, its data are crucial to arguments about the detection and identification of decoupled nuclear explosions larger than 1 kiloton. Using the above data for the 1971 and 1976 Azgir explosions, magnitudes of 2.4 and 3.4 are obtained for fully decoupled nuclear explosions (DF = 70) of 1 and 10 kilotons at the same depth in salt at Azgir.

- Mill Yard was a U.S. nuclear explosion detonated in 1985 at the Nevada Test Site (NTS) in soft rock in a hemispherical cavity of radius 32 feet (11 m) (Garbin, 1986; Murphy, 2009). The amount it was decoupled is uncertain (Stevens et al., 1991, Sykes, 1996, Murphy, 2009). A cavity suitable for full decoupling of 1 kiloton in the same rock type would have to be much larger (about 40-m radius), a significant engineering achievement compared to the mining of the Mill Yard cavity (a factor of 96 in volume). Purging of the Mill Yard tunnel released 5.9 curies of radioactive material into the atmosphere (OTA, 1989 p.4). Two other explosions in cavities of the same size but of somewhat greater yield may have been decoupled but by small amounts (Stevens et al., 1991).

Computer calculations of decoupling

Computer codes have been used over the past 50 years in attempts to estimate decoupling factors (DF) for cavities of different size for explosions in salt and hard rock (e.g., Stevens et al., 1991; Glen and Goldstein, 1994; Murphy, 1996; 2009). The Seismology Subcommittee judged that some of those calculations for salt have overestimated DF for fully decoupled nuclear explosions and all of them for partially decoupled tests. Just prior to the Sterling test in 1966, a DF of about 125 was computed for it, whereas 72 was observed (Figure E-1). More recent code calculations that were constrained to fit the decoupling factor of 72 for Sterling (Glen and Goldstein, 1994; Murphy, 2009) give a DF of 50 to 65 for the 8-10 kiloton partially decoupled explosion at Azgir. However, actual observations of DF for it at large distances (Figure E-1) are significantly smaller–12 to 15. The estimates of DF made at close distances in Figure E-1 have a much larger uncertainty but still fall well below the two code calculations.

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[5] The details of the decoupling factor calculation are given in Sykes (1996). Note that the magnitude of these Azgir events are slightly smaller (by ~0.2 magnitude units) than predicted by the standard magnitude-yield formula given on page 144 due to the greater than normal depth of the events. However, this depth effect affects both the 1971 and 1976 event equally, so the magnitude-yield formula can still be used to determine the partial decoupling factor from the difference between measured magnitudes of the two events given their announced yields. See Sykes (1996) for further discussion.

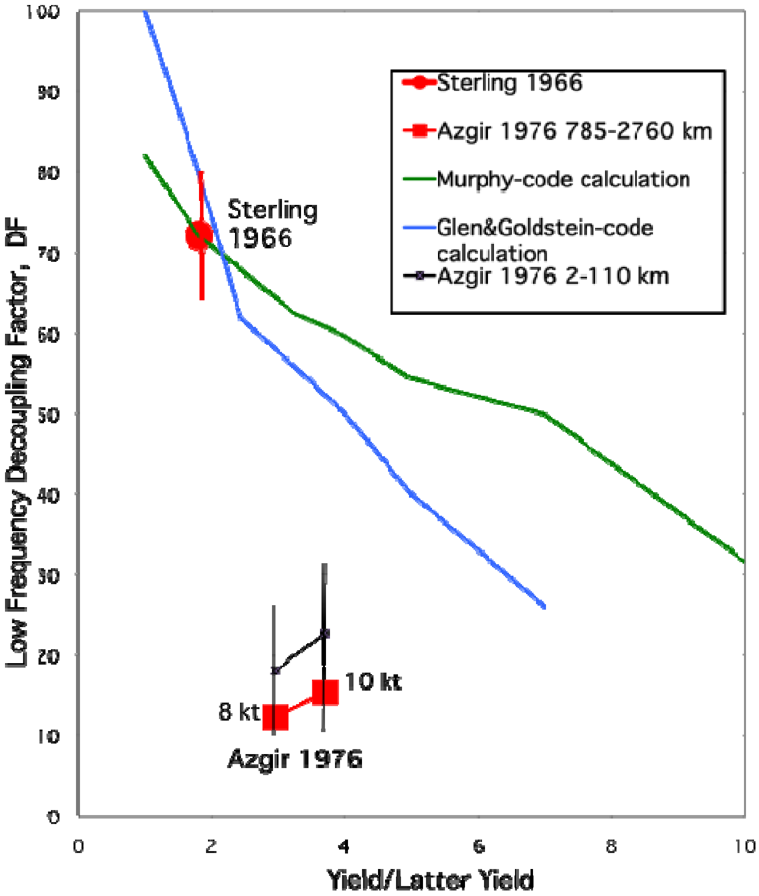

FIGURE E-1: Decoupling factor (DF) for the Sterling and Azgir nuclear explosions in salt, and code calculations by Glen and Goldstein (1994) and Murphy (2009) as a function of the yield divided by the maximum yield allowed according to the Latter criterion for containment. That criterion states that the pressure on the cavity wall should be no larger than 0.5 ρgh, where ρ is the average rock density, g is gravitational acceleration, and h is cavity depth. Because most rocks are weak in tension and strong in compression, the criterion is such as to keep the rock surrounding a cavity in compression during and soon after an explosion. Full decoupling involves keeping the surrounding rock in the elastic domain so that no permanent deformation occurs. The uncertainties (one standard deviation) in the decoupling factors for the Azgir partially decoupled explosion obtained at stations at distances between 785 and 2,760 km (491 and 1,725 mi) (Sykes, 1996) are comparable to the size of the two red squares, whereas they are much larger for the closer measurements between 2 and 110 km (1.2 and 69 mi), as shown by the vertical black bars (Glen and Goldstein, 1994). SOURCE: Adapted from Glen and Goldstein, 1994; Murphy, 2009; and Sykes, 1996

Observed decoupling factors for the Cowboy chemical explosions in salt in 1959 also are smaller than those from code calculations (Murphy, 2009). These overestimates are likely attributable to the properties of salt in the region surrounding the cavity being different from those derived from measurements of physical properties either on a laboratory scale or on salt that has not been subjected to a previous nuclear shock or to solution mining. Different decoupling factors as a function of cavity size for several rheological models of the strength of the salt surrounding the Salmon and Azgir cavities have been calculated by Glen and Goldstein (1994) and Murphy (1996, 2009). The uncertainty is expressed by the sub-title of Goldstein and Glen's (1993) "Simulation is easy. Prediction is difficult!"

In their thorough re-examination of the data from Salmon and Sterling, Denny and Goodman (1990) find that the Sterling explosion was nearly fully decoupled, even though its yield exceeded the Latter criterion by 1.8 times (0.9 times the overburden pressure). They conclude that decoupling factors larger than about 70 could not be obtained by further increase in cavity size. It is clear from the data in Figure E-1 that the decoupling factor for explosions in salt drops precipitously between 1 and 2 times the overburden pressure (2 to 4 times the Latter criterion). Denny and Goodman also find that nonlinear effects of the Sterling explosion extended outward to about 80 m, much larger than its cavity radius of 16.7 m, but that the seismic corner frequency was closely related to cavity size. Hence, more attention needs to be paid to the actual data on cavity size and decoupling factors for the Sterling and Azgir explosions (Figure E-1) and to the analyses of Denny and Goodman than to the more vague concept of "an elastic radius."

Claims such as that by Stevens et al. (1991) that very large decoupling factors can be obtained for explosions that are overdriven[6] by large amounts in salt compared with those for Sterling, are not supported by the data of the 1976 Azgir nuclear explosion and the 1961 Cowboy chemical explosions. Murphy (2009) acknowledges this misfit for overdriven explosions whose yield is too large for the size of its cavity (i.e., the pressure on the cavity wall exceeds the Latter criterion). A prospective cheater relying on the single data point for the small Sterling explosion and code calculations for salt either would be forced to make very conservative assumptions about decoupling or forego that mode of clandestine testing.

Decoupling factor at high frequency

Decoupling leads to a seismic signal that looks like that of a smaller explosion. So, for example, a 10 kt explosion looks basically like a fully coupled explosion of 150 tons using a decoupling factor of 70, if such large cavities could be achieved at depth. Figure E-2 compares the computed amplitudes (on the vertical axis) as a function of frequency (on the horizontal axis) of coupled and fully decoupled nuclear explosions, each with yields of 10 kilotons. The two spectra are nearly flat (horizontal) at low frequencies and then drop off (decay) at frequencies higher than what is called the "corner frequency." The corner frequencies in this case are 2 Hz for the coupled explosion and 12.5 Hz for the decoupled event; lower-yield explosions will have higher corner frequencies, as do earthquakes.

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[6] An overdriven explosion is one for which the pressure on the cavity wall places the surrounding rock, in this case salt, in tension. It results in partial decoupling.

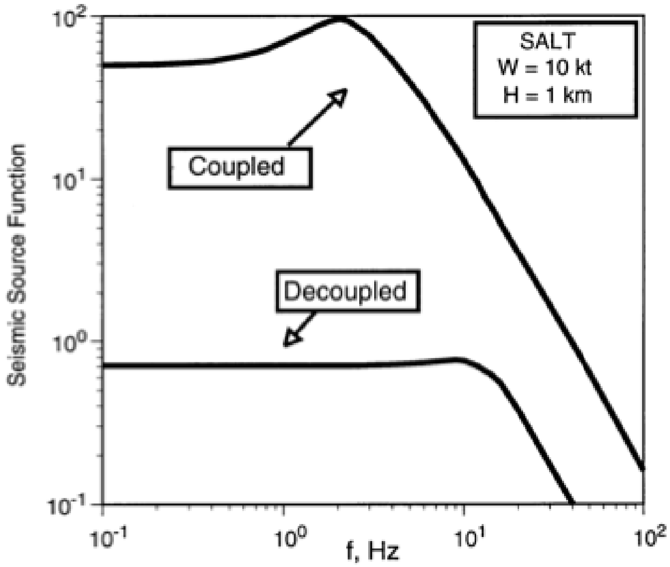

FIGURE E-2: Comparison of computed seismic source functions for various frequencies (f) in Hz (cycles per second). W = yield and H = depth. SOURCE: Murphy and Barker, 1995

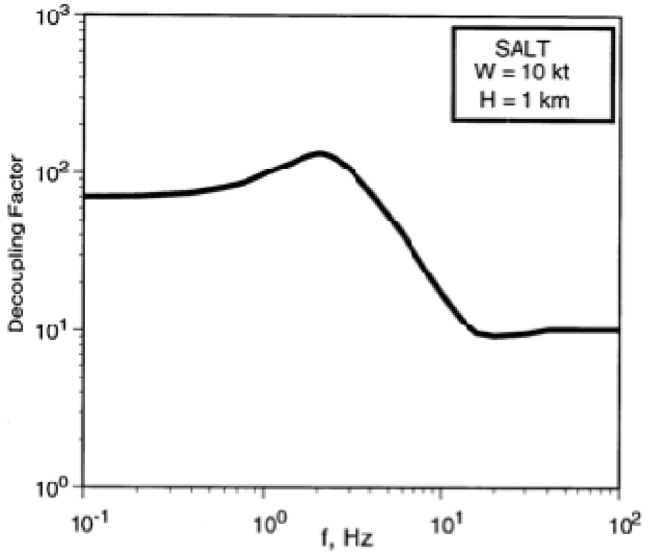

FIGURE E-3: Decoupling factor (DF) as a function of frequency for the fully decoupled explosion in Figure E-2 compared with that of the well-coupled explosion. W = yield and H = depth. SOURCE: Murphy and Barker, 1995

Figure E-3 compares the amplitude ratio (i.e., the decoupling factor, DF) for the decoupled and coupled calculations shown in Figure E-2. DF is about 70 at low frequency and drops to about 15 at a frequency of about 10 Hz (cycles per second). For explosions of 1 kt, the drop to a DF of 30 would occur at about 15 Hz and to a DF of 10 at about 25 Hz. Scaling the corner frequency of Sterling to 1 kiloton gives 25 Hz (Denny and Goodman, 1990). Modern seismic instruments, especially those at regional distances from seismic sources, record high-frequency signals. Frequencies up to 20 Hz are often recorded for regions characterized by efficient propagation of seismic waves—such as most of Russia, the areas near the Chinese and Indian test sites, and all of North Korea. Hence, for areas characterized by efficient propagation of seismic waves of high frequencies, the detection of decoupled tests of 1 kiloton and larger can be accomplished because a well coupled test whose yield is 1 kiloton divided by 70 (that is, about 15 tons) can be detected in such regions. In fact, it may not be necessary to go to frequencies above the corner frequency where the DF is less in order to see decoupled explosions if the equivalent fully-coupled explosion is detectable at that yield. For example, as discussed in Appendix D, a 15-ton shot (1kt decoupled by 70) is detectable at Novaya Zemlya using the IMS. Kim and Richards (2007) describe detections, across a broad band of frequencies, of chemical explosions whose yield was just one or two tons, at distances of about 300 km (188 mi) in northeast China just to the north of North Korea.

Decoupled testing in existing cavities created by past explosions in salt

Both the decoupled 1966 Sterling and the partially decoupled Azgir nuclear explosions were detonated in cavities in salt domes created by well-coupled nuclear explosions. Salt is one of the few Earth materials in which a cavity produced by a nuclear explosion is not likely to collapse on a time scale of months to years. Nevertheless, it takes a fully coupled explosion about 14 to 20 times larger to create a cavity in salt suitable for conducting a subsequent, fully decoupled explosion in it. Hence, a past explosion in salt of 1 kiloton is suitable for conducting only a fully decoupled test of 0.07 kilotons (70 tons) or smaller. While the U.S.S.R. conducted a number of fully coupled nuclear explosions in thick salt deposits (OTA, 1989; Sultanov et al., 1999), all of the possible sites of cavity-producing explosions in salt of 2 kilotons or larger are known and can be monitored readily. All are located in regions of very low earthquake activity. Thus, a seismic event at or near one of those sites would be suspicious immediately and receive intense scrutiny.

All 8 cavities created by past Soviet explosions in salt that are suitable for fully-decoupled explosions of one kiloton (and up to a maximum of 4.2 kilotons) are located either at Azgir in Kazakhstan or Bukhara in Uzbekistan (Sykes, 1996). All explosion-produced cavities in salt in the Russian Republic are suitable only for fully decoupled tests of 0.5 to 0.9 kilotons or smaller. Hence, the breakup of the Soviet Union greatly limited possible opportunities for conducting future decoupled nuclear explosions by Russia in explosion-produced cavities because of the exclusion of regions in Central Asia.

Testing in cavities in salt constructed by either solution or conventional mining

Turnbull (1995, 2002), Leith (2001), and others propose that large cavities could be used for decoupled testing with yields much larger than 1 kiloton. It is generally agreed that to fully decouple a 5-kiloton explosion in salt at a depth of about 3,000 feet (900 meters) a spherical cavity with a diameter of about 240 feet (73 meters) is required. Obviously, this would entail a substantial construction effort.

Very large cavities have been created in salt domes by conventional and solution mining (Berest and Minh, 1981; Sykes, 1996; Leith, 2001), mainly for storage of gas, oil and toxic waste. Salt domes, sometimes called salt diapirs, are large bulbous geological structures consisting mainly of the mineral halite (sodium chloride) but often with up to 5 to 10 percent of other minerals (Leith, 2001). Salt domes are known traps for petroleum. The economic value of salt deposits has led to their being mapped extensively and either described in the open literature (e.g., Zharkov, 1984) or held as proprietary data by petroleum companies.

The Pre-Caspian depression, which contains the world's largest known concentration of salt domes, is located mainly in Kazakhstan but extends into adjacent parts of Russia. Another huge area of salt domes is found along the Gulf coast of the United States. In terms of countries of proliferation concern with respect to evasive testing, Leith (2001) reports other widespread salt deposits in China and Iran, limited deposits in Pakistan (Davis and Sykes, 1999), very limited quantities in India and Israel, and no known salt deposits in North Korea, a country of very old crustal rocks. Significant thicknesses of salt for decoupled testing are not present at the following test sites: Novaya Zemlya, Russia; Lop Nor, China; Pokharan, India; Pakistan (two sites); and France's now closed test site in the Pacific.

Thick beds of salt that have not been deformed into salt domes are known in other parts of Russia, especially to the north of Lake Baikal, and in some of the now independent countries of the former Soviet Union (Zharkov, 1984; OTA, 1989). Bedded salt, however, is generally not as favorable for the construction of very large underground cavities because salt is typically interbedded with other rocks such as dolomite, anhydrite, gypsum, limestone and sandstone and sometimes with weak layers of potash. Salt domes typically contain fewer of these sedimentary rocks, making them more suitable for construction of very large cavities.

Solution mining is the least expensive method for either mining salt itself or forming large cavities for other uses. In solution mining, fresh water is pumped in a pipe that extends from the surface into a salt formation at depth. A mixture of salt and water (brine) is pumped back out in another pipe. This avoids constructing tunnels and shafts as in conventional mining. The U.S. Strategic Petroleum Reserve is stored in large cavities created by solution mining at Bryan Mound, Louisiana. Large pumps, tanks and other equipment are quite visible at that site. Brine in very large cavities created by solution mining has rarely been pumped out and replaced by air. An explosion in a brine-filled cavity would be well coupled, not decoupled. Emptying a large commercial cavity of this type without replacing its content (e.g., oil or pressurized gas) by brine or seawater is strictly discouraged or forbidden because these expensive and fragile structures may collapse. Relatively little is known about the strength of salt near the wall of a cavity formed by solution mining. Hence, extrapolating the properties of salt in the region surrounding a cavity formed by a nuclear explosion such as Salmon to a solution-mined cavity is uncertain.

Disposal of brine is a major problem because a rule of thumb in the industry is that the solution mining of 1 cubic foot of salt requires about 7 cubic feet of injected fresh water (Leith, 2001). In some locations, the fresh water could be pumped from an aquifer, and the resulting brine pumped into another aquifer perhaps at greater depth, thus avoiding large surface flows of water and brine. Having enough fresh water to construct a very large cavity by solution mining would be a major problem for salt deposits in arid parts of Iran, the Middle East, northwestern China, Pakistan and India.

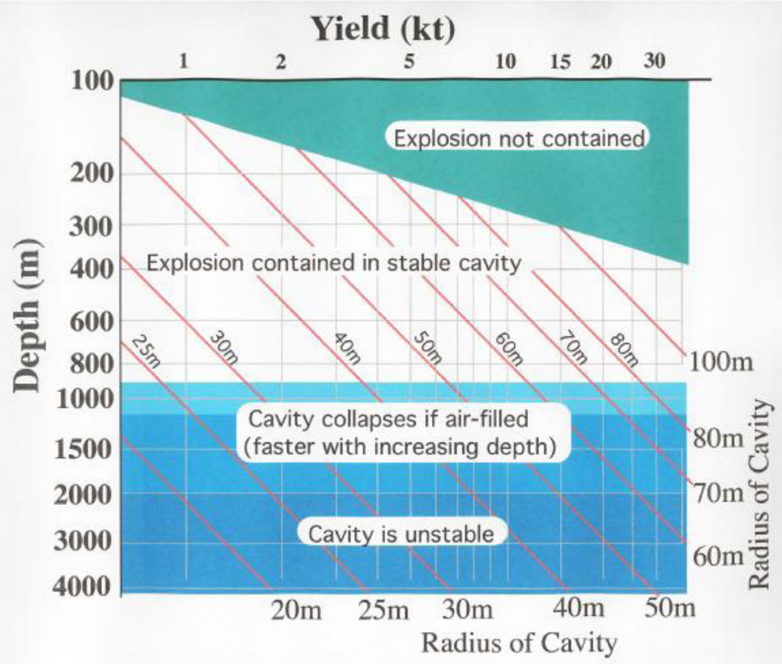

FIGURE E-4: Stability range for an air-filled cavity in salt. Depth range is bounded at the shallow end by need for containment of a decoupled nuclear explosion and at the deep end by the need to keep the cavity open long enough to conduct explosion. Diagonal lines indicate minimum cavity radius (in meters) required for full decoupling. A given size of cavity is suitable only for smaller yields as depth decreases. SOURCE: Modified from Davis and Sykes, 1999

Unlike most rocks, salt deforms at relatively shallow depths in the crust of the earth, which limits the *depth* at which cavities can be constructed for clandestine testing (Figure E-4). Air filled cavities in salt typically are not stable at depths greater than about 2,900 to 4,200 feet (880 to 1,280 meters) (Berest and Minh, 1981). Those depths are a function of the temperature gradient in the Earth and the presence of other minerals including small amounts of water. Cavities in salt cannot be *shallower* than that needed to ensure containment of decoupled explosions. The 1966 Salmon and the 1976 Azgir explosions were detonated at nearly optimum depth, about 3,000 feet (about 900 meters), so as to insure both containment and cavity stability. Larger cavities would have been needed to ensure containment if those explosions had been conducted at shallower depths. Leith (2001) references large cavities created by solution mining in the former Soviet Union and Germany at depths to 200 feet (60 meters). Though large, their very shallow depth would not ensure containment for a decoupled explosion larger than a very small fraction of a kiloton. When the United States was testing in Nevada, containment policy since 1970 was to detonate explosions of any yield at depths of at least 600 feet (183 meters) (OTA, 1989).

A number of very large cavities in salt at depths greater than about 3,000 feet (900 meters) have either totally or partly collapsed (Sykes, 1996; Leith, 2001). Fifteen nuclear explosions with yields of about 3 to 15 kilotons were conducted during the 1980s at depths of 3,000 to 3,600 feet (900 to 1,100 meters) in bedded salt to the north of Astrakhan, Russia, near the mouth of the Volga River. All were intended to create cavities for the storage of gas condensates from nearby gas fields. Most, and perhaps all, of the cavities had completely closed within several years of the explosions that created them.[7]

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[7] Written communication to L. Sykes from W. Leith. September 7, 2001.

Salt domes are commonly capped by sedimentary rocks up to a few hundred meters thick. Most cap rocks are highly fractured (Leith, 2001) from the deformation that results from the formation of salt domes. Ground water often circulates in cap rocks at shallow depths. Rock salt (halite) is often considered to be a viscous material that never deforms by brittle faulting. Fractures and faults, however, are observed very locally in some salt domes (Davison, 2009). A potential evader would need to select a salt dome whose top and deformed cap rocks are well below the surface.

Earthquakes are very rare in most areas of thick salt deposits, including those in Russia, the Ukraine, the Pre-Caspian depression of Kazakhstan and the Gulf coast of the U.S. Large chemical explosions are not used in salt mining. Hence, the near absence of those seismic events makes monitoring of those areas for clandestine testing relatively easy. Earthquakes do occur in the vicinity of a number of salt deposits of Iran. Much is known about the geology of Iran, including the locations of salt deposits, from petroleum exploration and other geologic mapping over the last century. Iran, a moderate-size country, can be monitored using seismic stations in several surrounding countries.

One decoupling option would be to use an abandoned salt mine for decoupled testing. Such mines, however, typically have exploratory drill holes and other openings, all of which must be known and sealed before a nuclear-explosion test so that they are not conduits for radioactive materials to the surface. An early plan for permanent disposal of radioactive waste from commercial nuclear reactors in an abandoned salt mine near Lyons, Kansas, was cancelled in part because all previous boreholes had not been cataloged and containment could not be assured.

No decoupled nuclear explosions are known to have been conducted in cavities created in salt by either solution or conventional mining. Hence, a country wanting to conduct a clandestine test in such a manner would have to be wary about containment of bomb-produced radioactive isotopes, cavity stability, and detection by the much-increased capabilities of seismology and by the various national technical means available to the United States. The very small levels of earthquake activity in most areas of thick salt deposits make them relatively easy to monitor. Only the United States and Russia are known to have conducted decoupled tests. The capabilities of other countries to conduct decoupled tests in total secrecy must be questioned given their lesser testing experience (if any), their limited testing in a variety of rock types and less experience with containment.

Testing in cavities in hard rock

Hard rock is much more abundant globally than are thick salt deposits. Lacking salt, it is the medium in which construction of large cavities would have to be undertaken for clandestine testing by North Korea and at the Russian, Chinese, Pakistani, and Indian test sites. Mining of large cavities in hard rock, however, is much more difficult and expensive than is cavity construction in salt. Secret disposal of the material excavated is likely to be more difficult compared with the disposal of salt brine. The volumes and diameters of the largest existing cavities in hard rock are much smaller than those formed by solution mining of salt. Cavities of the size used for the tiny Mill Yard explosion are far smaller than those needed for full decoupling of explosions of even a fraction of a kiloton in hard and soft rock.

Many engineering reports on the construction of large underground openings emphasize that hard rock masses are seldom monolithic but are penetrated by numerous joints, faults and other discontinuities on many length scales. Traditional continuum codes (computer simulations) are not sufficient for simulating dynamic block motion for underground nuclear explosions in such media (Heuzé et al., 1991). The failure of codes to fit both data points for the two decoupled explosions in salt—Sterling in 1966 and Azgir in 1976 (see Figure E-1)—indicates that similar calculations for hard rock are likely to be more unreliable. Faults and joints on the scale of 10 to 1,000 meters (30 to 3,000 feet) also present a major problem for containment of radioactive products produced by a nuclear explosion, especially for the containment of noble gases like xenon. Faults and cracks in hard rock (in contract to salt) do not heal after a nuclear explosion. Containment methods perfected for fully-coupled explosions are largely irrelevant for decoupled explosions. The rock is not liquefied by the shockwave, and leaks are far more likely.

Construction of spherical cavities in hard rock that are large enough for full decoupling of explosions over 1 kt is expensive and requires technological sophistication not widely available (Leith, 2001). Leith's estimate, however, assumes a 20 meter (66 foot) radius for full decoupling of 1 kt in hard rock at a depth of about 3,000 feet. Murphy (2009) now concludes that the required radius is nearly identical for *both salt and hard rock*. Using 25 rather than 20 meters, which we identified earlier for salt, results in a volume increase of a factor of two and hence in the above construction results in difficulty starting at 0.5 rather than 1 kt.

Large *non-spherical* cavities in hard rock of the same volume are easier to construct and have been proposed for clandestine testing (Stevens et al., 1991; Leith, 2001; Murphy, 2009). The surface area of non-spherical cavities, however, is greater than that of a sphere of the same volume. Hence, the chance that more faults, cracks and joints would be encountered at the surface of a non-spherical cavity increases the chance that radionuclides could escape and be detected. The shortest dimension of non-spherical openings in hard rock will experience the largest non-elastic pressure pulse compared with that experienced on the wall of a fully decoupled nuclear explosion of the same size in a spherical cavity.

A number of the large cavities in hard rock described by Leith (2001) are too shallow for containment to be assured except for an explosion with a yield of a small fraction of a kiloton. One example is the underground skating arena in hard rock created in Norway for the 1994 Winter Olympics. Whereas that arena has an unsupported span of 200 feet (61 meters), the depth below the surface of its top is only 82 to 165 feet (25 to 50 m). Those depths are too shallow for containment of radioactive products if a similar cavity were to be used for decoupled nuclear testing. Room-and-pillar mines in hard rock and salt also are poor choices for decoupled testing because damaged or destroyed pillars may well result in collapse of underground openings.

Turnbull (1995) claims that nuclear explosions were conducted evasively by the Soviet Union in mines, one in 1972 on the Kola Peninsula and a second in the Ukraine on September 16, 1979. But they have, in fact, been detected. In his review of Soviet peaceful nuclear explosions (PNEs), Nordyke (1975) describes a proposed ore-breaking project using a 1.8-kiloton PNE. A Soviet list of PNEs (Sultanov et al., 1999) contains a 2.1 kt explosion on September 4, 1972, on the Kola Peninsula in a well-known mining area. It was recorded by 47 open stations with a magnitude of 4.6. Hence, it was well coupled, not decoupled.

In 1992, *The New York Times* reported a nuclear explosion of 1/3 kiloton at noon on September 16, 1979, in a mine at Yunokommunarsk, Ukraine. Sultanov et al. (1999) list it as occurring in sandstone within a coal mine with a yield of 0.3 kt. From seismic arrivals at the NORSAR seismic array, Ringdal and Richards (1993) computed an event time at noon Moscow time and a magnitude of 3.3. They state that it would have been much better recorded if it had occurred in 1993, when an advanced regional seismic array was in operation in northern Europe. It would be even better recorded and located today. The yield computed for magnitude 3.3 was about 3 times smaller than if it had occurred in hard rock. Its smaller magnitude is reasonably attributed to its occurrence in soft rock, not to decoupling. Explosions in coal and similar soft rocks do not produce as large seismic waves as those in hard rock.

Decoupling factors of about 20 to 40 have been observed for chemical explosions in hard rock that range in size from a few pounds to about 10 tons. There remains uncertainty in how to map the different energy density of chemical explosions into a nuclear decoupling factor. This uncertainty complicates hard rock decoupling scenarios for a potential evader. Salt is the only medium in which a decoupling factor as large as 70 has been obtained for chemical explosions in underground cavities. Thus, a maximum decoupling factor for hard rock of 40, not 70, seems more appropriate to assume for monitoring at 90 percent confidence. A country not wanting to be caught cheating likely would need to use a smaller factor, say one not larger than 10 to 20, and not to attempt decoupled testing larger than 500 tons (half a kiloton) in hard rock.

Evaluation of the cavity-decoupling scenario as the basis for a militarily significant nuclear test program therefore raises a number of different technical issues for a country considering an evasive test:

1. Is there access to a region with appropriate geology for cavity construction?
   - Is that geological medium nearly homogeneous on a scale of hundreds of meters?
   - Can cavities of suitable size, shape, depth and strength be constructed clandestinely in the chosen region?
2. For a cavity in salt formed by solution mining:
   - Is enough water available?
   - Can it be pumped out and the brine disposed clandestinely--eight times the cavity volume, plus the final brine fill?
   - How should the very limited experience with conducting decoupled nuclear explosions in salt be taken into account?
   - Can decoupling factors as high as 70 be attained for yields much larger than sub-kiloton (i.e., larger than the 1966 Sterling test)?
   - Can the layered properties of rock sequences for bedded salt be dealt with?
3. For a cavity in hard rock:
   - Can mined rock be disposed of clandestinely?
   - Can a country afford the price of mining a large cavity in hard rock?
   - Can uncertainties in rock properties and in orientations and magnitudes of principal stresses be dealt with?
   - Can presence of joints and faults in hard rock be detected and dealt with?
   - Can flow of water into cavity—in either hard rock or salt—be dealt with?
   - Can cavities that depart significantly from a spherical shape[8] be used?
   - Should a decoupling factor no larger than 10 to 20 be assumed?
4. Can collapse of cavity during construction and decoupled test be avoided?
   - Can surface deformation potentially detectable by interferometric synthetic aperture radar (InSAR) both during and after construction and following the test be minimized?
5. Can radionuclides be fully contained from a decoupled explosion?
   - Take into account that noble gases can be detected today at much smaller concentrations than a decade ago.
   - Take into account that radionuclides have leaked from many previous nuclear explosions in hard rock at Novaya Zemlya and eastern Kazakhstan and the few in granite at the Nevada Test Site.
6. Can the site be chosen to avoid seismic detection and identification, given the detection thresholds of modern monitoring networks and their capability to record high frequency regional signals?
   - Can the limited practical experience with nuclear tests in salt, and very low-yield chemical explosions in hard rock, be extrapolated to predict the signals associated with nuclear testing in cavities in hard rock?
   - Can the size of a test be made small enough to deal with future advances in detection and identification capabilities?

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[8] Dimensions that differ by more than 1:4 (Murphy, 2009).

7. Is there such a region that is suitably remote and controllable, and that can handle the logistics of secret nuclear weapons testing?
   - Can secrecy be successfully imposed on all of the people involved in the cross-cutting technologies of a clandestine test program, and on all who need to know of its technical results?
   - Can the tester avoid compromising security by conducting a nuclear test in a region containing a hostile ethnic group or a civil war? Can the test be conducted outside one's own territory?
8. Can nuclear explosions of large enough yield be carried out secretly, and repeated as necessary, to support the development of a deployable weapon?
   - Can those carrying out the decoupled test be sure that the yield will not be larger than planned, and thus only partially decoupled?
   - Can a minimum of drill holes, cables, and specialized equipment be used and yet obtain necessary information about the characteristics of nuclear device(s).
   - Can the site be cleaned up before an on-site inspection team arrives?
9. Can a clandestine test in a mining area be hidden in one of a series of ongoing large chemical explosions?
   - Can suitable rock for a decoupled test be found below coal, other minerals and sedimentary rock in which large chemical explosions are used in mining?

Mine Masking

The *2002 Report* briefly described the possibility of evasive nuclear-explosion testing in an active mining region. Many types of mining operations routinely use chemical explosives, sometimes in impressively large amounts (exceeding ten kilotons of chemical explosive for some shots, and annual totals amounting to megatons of explosive per year for the largest industrial countries). An issue of concern in the early 1990s was whether large mine blasts might generate seismic signals in such numbers that efforts at CTBT monitoring for nuclear explosions could be overwhelmed, but it later became understood and accepted that the commercial purpose of mine blasting entails practices that greatly reduce seismic amplitudes and only a small fraction of mine blasts would even be detected. The issue with mine-blast signals then became whether detectable blasting activity could be used to mask or disguise the signals from an underground nuclear explosion. This section provides further details, additional references to papers and a website that describe relevant aspects of the seismic signals from chemical explosions, and some specific mining regions where blasting activity is detected at monitoring networks, and summarizes assessments of the size of the largest underground nuclear explosion whose seismic signals might be successfully masked by mine-blasting.

To estimate the overall scale of mine blasting Richards et al. (1992) surveyed blasting operations in the mining industry (emphasizing the United States, with operations in Russia and Europe being comparable) and concluded: “The main point…from the perspective of those concerned with nuclear explosion monitoring and the question of discriminating between chemical and nuclear explosions, is that a large industrialized country can be expected to carry out large numbers of chemical explosions.” The industry would call a shot larger than 50 tons “large,” and on the order of 30 such shots occur each day in the United States, including one at 200 tons or even larger. Several shots at the kiloton level occur each month, and some amount to more than ten kilotons. A key point is that almost all industrial shots larger than 1 ton are “ripple fired” with the total charge broken up into much smaller units, typically less than 100 kilograms (0.0001 kilotons) of chemical explosive, that are fired in sequence to achieve the commercial purpose of breaking or moving large amounts of rock. For the largest chemical explosions, the sequence of separate blasts typically takes tens of seconds to execute. A net effect is great reduction in amplitude of seismic signal compared with the strength of nuclear explosion signals, where all the energy is released almost instantaneously.

Khalturin et al. (1998) surveyed chemical explosion activity on the territory of the former Soviet Union, finding that this reduction in signal strength (compared to a single-fired shot, or an underground nuclear explosion) was by factors typically in the range of 30 to 100. They wrote that "The reason for the inefficiency of generating seismic signal is presumably because the usual commercial purpose of chemical explosions entails the need to fracture rock into small pieces, which necessitates firing practices (such as ripple firing) in which much of the explosive energy goes into rock fragmentation. A smaller fraction is then radiated seismically than would be the case for a well-coupled single fired shot" (p. 13). They reported a small number of locations where the reduction is less, around a factor of 3 for quite large chemical yields (several hundred tons), and noted that "Such explosions, which appear to be uncommon and declining as blasting practices are modernized, may require special attention in the context of verification of the Comprehensive Test Ban Treaty" (p. 1).

Concerning the numbers of potentially problematic mine blasts, Khalturin et al. (1998) also wrote that: "… there are a limited number of regions in which mine blasting is seismically detectable over large distances. The Kuzbass mining region of western Siberia, Russia, and the region near Abakan farther to the east, appears to be associated with explosions with magnitude greater than 3.5 that are likely to be detected a few times each month at considerable distances" (p. 13).

Recognizing the potential for ambiguity in interpreting seismic signals both from large mine blasts and mine ground failure (such as cavity collapse), a working group looked at this problem in the late 1990s. The working group created a draft report in 1997 that was reviewed by the National Research Council in 1998 (NRC, 1998). The working group used the NRC review to produce a final document (Chiapetta et al., 1999). As noted in that report the CTBT encourages the voluntary reporting of any industrial explosion greater than 300 tons and has a provision for consultation and clarification designed to address questionable events in an unobtrusive way. The report also notes that there are discrimination techniques to identify large mine collapses and ripple fired mine blasts, though these are not foolproof. Finally the report notes that as the mining industry makes greater use of precision timing systems in conducting ripple firing, which allows better control over the rock fragmentation, the overall size of many of these mine blasts may be lowered to less than magnitude 3.5.

The number of mines where there are routine blast events greater than magnitude 3.5 is limited. We examined the CTBTO's Reviewed Event Bulletin (REB) for 2007-2008 to look for regions of routine blasting that have seismic signals greater than 3.5. Figure E-5 shows six regions that were identified because the seismic events all occur during daylight hours, whereas earthquakes are more random and occur equally during the night and day. These regions each contain multiple large open pit mining operations easily visible in Google Earth. Table E-1 gives the characteristics of these regions.

The coal mining region in Wyoming with large mine blasts is very well known (e.g., Chiapetta et al., 1999; Arrowsmith et al., 2008; Zhou et al., 2006). The mine events often have very different characteristics from earthquakes making them easy to identify. For example, the largest event, with IDC maximum likelihood of m_b = 3.9, has a very low local magnitude (REB ML = 3.5, USGS ML = 3.2), very different from earthquakes. The repeating nature of mining events also allows the use of waveform correlation methods to obtain very precise relative time, location, and size differences between events.

The United States has set a good example by providing publically available information about seismic events associated with mining. Since the late 1990s, the U.S. Geological Survey (USGS) has documented U.S. mine blasts detected seismically, including those that have been reported by the REB of the CTBTO. The USGS website[9] describes this activity, gives links to archives of information on detected mining blasts, and notes that the work is done in the context of confidence building measures associated with the CTBT.

Authorities in both Russia and China have provided information on specific very large blasts on their territories.

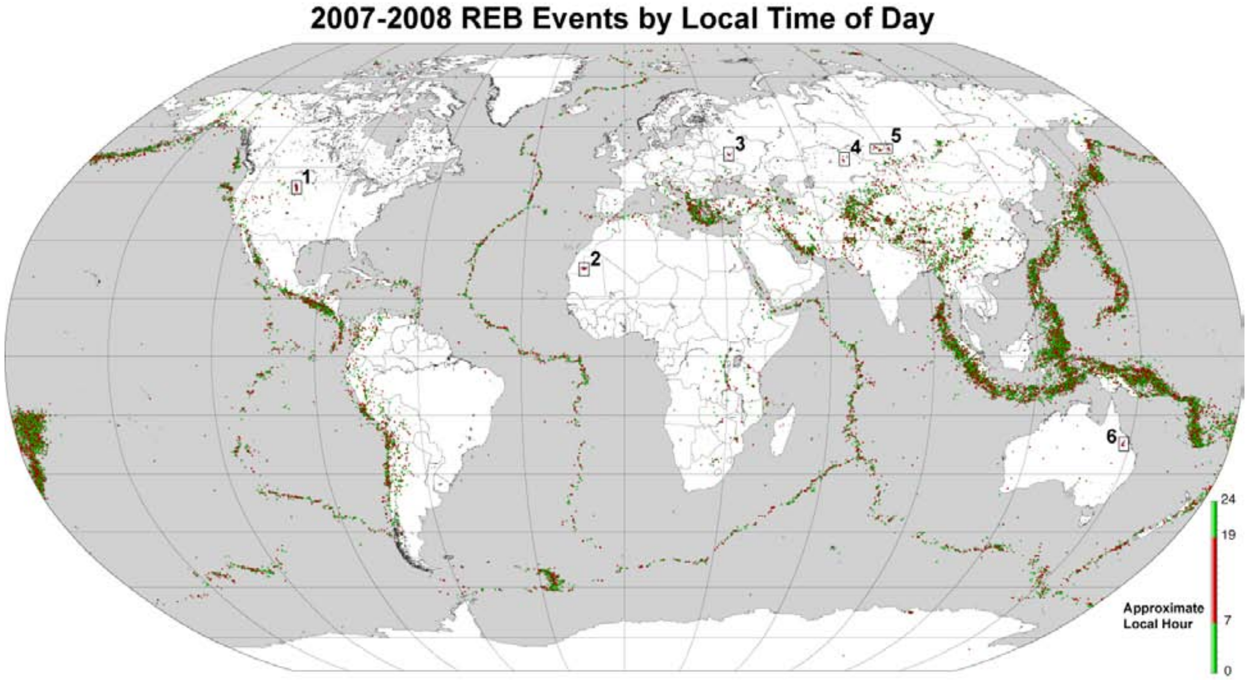

FIGURE E-5: Map of 41,728 Reviewed Event Bulletin (REB) events from 2007-2008 with depth < 50 km (31 mi) and $m_b > 0$ colored by time of day they occurred. Approximate daytime events are shown in red, and approximate nighttime events are shown in green. Six prominent mining regions are marked. SOURCE: William Walter, Seismology Subcommittee member

The REB m_b values in the last row of Table E-1are typically derived from a single IMS station and hence may be unrepresentative of the magnitudes that would be reported by a network of detecting stations. Station magnitudes typically exhibit a scatter in values about the mean value, so that use of only one station that rises above noise levels usually results in a magnitude that is biased toward high values.

With respect to mine masking, mines typically adopt locally-appropriate practices of blasting so that the infrastructure of the mine and its environs are not stressed too much by local vibrations. Thus part of the work of monitoring is to compare new signals against an archive of previous signals from the same region. But if an underground nuclear test in a mining area were carried out at nearly the same time and place as a mine blast typical of the region, then what magnitude level of signals might result? And what are the possibilities for concealment, via this approach, of a treaty violation? Answers can come from taking examples of signals from large mine blasts, and signals from small underground nuclear explosions, then adding them together before subjecting them to the methods used to discriminate between various types of seismic events. What is typically found is that the maximum size of the identifiable waves (for example,

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[9] See: *http://earthquake.usgs.gov/earthquakes/eqarchives/mineblast/*.

the *P*-waves) from the mine blast is about that expected from individual sub-blasts (commonly called "delays"), and these amplitudes are spread out over a longer time in seismograms. For this reason, the use of mine-blasts for masking nuclear explosion signals, though they might afford some possibilities, are not very effective for concealing large releases of energy. The seismic signal from an underground nuclear event is an expression of the instantaneous release of nuclear energy, and unless the yield is very small, it stands out in comparison with the size of the energy released in a sub-blast "delay."

TABLE E-1: Example Mining Events in the 2007-2008 REB Catalog.

Mining region in Figure E-5	**1**	**2**	**3**	**4**	**5**	**6**
Region, Country	Wyoming, USA	Zouirat, Mauritania	SW Russia	Northern Kazakhstan	Siberia, Russia	Eastern Australia
Approximate location	43°N 105°W	23°N 12°W	52°N 35°E	51°N 74°E	53-55°N 85-92°E	22°S 148°E
Mineral Resources	Coal	Iron	Coal	Various	Various	Coal
Number of events in REB 2007-2008	250	22	34	12	157	33
Largest REB m_b (maximum liklihood)	3.9	3.7	3.6	3.5	3.9	4.0

SOURCE: Committee

A study of mine masking possibilities by Smith (1993) used several different examples of mine-blast seismograms together with single-fired explosion records and found a number of features that could be used to identify a simultaneous shot within a ripple-fired blast. He concluded that to conceal a single-fired deep detonation (depth is required for containment of radionuclides), the single explosive shot should not exceed 10 percent of the total explosive. This assumes an underground nuclear explosion that is well coupled. If the latter explosion were in a large cavity (which potentially might be possible to the extent that a large mining operation could include necessary equipment for creation of an underground cavity), then all the complication of executing a cavity-decoupled shot would be added to the procedures for carrying out the masking shot (that would itself—to the extent it were detected—attract the attention of monitoring agencies).

The discussion of mine-blasting and associated charge sizes is very different for deep mining and shallow mining. The latter is often called surface mining. The largest total charge sizes of chemical explosions in mining (on the order of kilotons) are associated with shallow mining, to remove surface layers in a procedure called cast-blasting (in which a long strip of sediments is thrown sideways) or to break up the uncovered target (usually coal, or iron ore). Surface mining operations differ from deep mining in that underground facilities and the dangers associated with them are absent, so that local ground vibrations can be larger. (Blasting in a deep mine is unusual if it involves more than 10 tons of explosive, because of the damage that large vibrations could do to local underground infrastructures.) Mine masking of an underground nuclear explosion would entail both shallow mining with its large charge sizes and deep mining to get a nuclear device down to levels at which its explosive energy would not open up paths for radionuclide releases. Thousands of people could be involved in such combined operations, and concealment of activities in a region that intrinsically draws attention because of its large seismic signals (from routine operations) would *per se* be a challenge.

If a large surface mining operation were to conduct a significant underground shot, the seismic signal would have different characteristics from routine surface shots, and such differences would be amenable to analysis through comparison of signals using correlation and other techniques. Thus for an evader, one of the main perceived advantages to mine masking—the fact that seismic signals from the region are common—is also a major disadvantage. This is because the routine signals allow very good calibration of the mine, hence permitting a detailed investigation into the nature of and differences between events. In addition, surface shots generate infrasound signals in ways that well-contained, deeply buried underground explosions do not. Infrasound signals in combination with seismic signals offer the potential to estimate the fraction of the shot that was underground.

Taking the events from Table E-1 as representative of the largest routine mining events, the REB $m_b = 3.9$ is about the magnitude of a single contained fully-coupled nuclear explosion of around 200 tons in a stable region to perhaps around 600 tons in tectonic regions (using the formulas of Murphy, 1996: $m_b = 4.45 + 1.0 \log (Y)$ for stable and $m_b = 4.05 + 1.0 \log (Y)$ for tectonically active).

Using the Smith (1993) criterion of 10 percent of total yield leads to estimates of around 20 to 60 tons for a masked shot in a large mine blast. Given these small yields, theoretical evasion scenarios often invoke the potential of decoupling the masked test. In this case, the mine is simply a cover for decoupled shots. The issues surrounding decoupled explosions are presented earlier in this appendix.

In addition to the seismic signals from blasting, mines can be seismic sources associated with a variety of other phenomena known collectively as “ground failures.” Caused principally by the introduction of cavities and thus stress-free surfaces at depth, where stresses previously had been large due to the overburden, these include coal bumps, mine collapses including pillar collapses, and rockbursts, whose seismic signals can be stronger than those from mine blasting (Chiapetta et al., 1999). Because neither the occurrence of these phenomena nor the size of their signals can be accurately predicted in time, they would not appear to afford practical opportunities for hiding the seismic signals from an underground nuclear explosion. Seismic signals from mine collapses have been intensively studied in the last 15 years because of specific examples of such events in 1995, for which the mix of seismic body waves and seismic surface waves initially seemed explosion-like (i.e., weak surface waves compared with the strength of body waves). Several authors have studied rock bursts and mine collapses with the goal of finding a method of discriminating their signals from those of underground nuclear explosions, and a reliable method has emerged that is based upon the distinguishing characteristic that in underground explosions the rocks in the vicinity of the shot point are pushed outward from the source, whereas in a rock burst or a mine collapse the rocks in the vicinity of the source move inward toward the source (see, for example, Bowers and Walter, 2002; Dreger et al., 2008). The polarity of seismic signals from a rock burst or mine collapse, whether for body waves or surface waves, is thus the opposite of that from an underground explosion.

Summary

Mining is a global multi-billion dollar industry that regularly uses large amounts of chemical explosives. The main economic purpose of industrial blasting is to fracture rock and expose resources. Therefore most large blasts are “ripple-fired,” spread out in time and space. This ripple firing reduces the seismic amplitudes and imparts characteristics to the signals that usually allows them to be distinguished from single-fired contained explosions. There are a limited number of mines in the world that routinely generate seismic events greater than REB m_b = 3.5, with the largest signals over the past several years being about 4.0. These large open pit mines take many years to develop and are visible by commercial satellite. Such mines and their blasting signals will be the subject of extra attention under the CTBT, noting that the Treaty provides means for voluntary reporting of shots greater than 300 tons (0.3 kilotons). Since the 1990s, the United States has voluntarily provided a separate list of mining events (times, locations, and magnitudes) through a website of the U.S. Geological Survey. The U.S. should encourage other countries with national seismic networks to do the same.

Work done in the 1990s indicates that a masked underground contained explosion would need to be smaller than 10 percent the size of the masking large mine blast. For the largest mine blasts, this leads to estimates for fully coupled shots of a few hundred tons of nuclear yield or less (decoupled explosions are covered in another section). For an evader, mining operations provide cover for extensive excavations needed to contain a nuclear test and reasons for seismic signals. However, mine operations that routinely produce large seismic events (magnitude > 3.5) can be among the best calibrated areas on Earth due to their past record of numerous events. The record of many routine signals allows techniques such as waveform correlation and joint seismic and infrasound analysis to provide ways to flag and identify unusual signals. Mines that routinely produce large seismic signals offer opportunities to better calibrate the seismic network for improved detection, location and identification.

Mine collapses that generate seismic signals greater than magnitude 3.5 are infrequent and are not easily controllable for masking purposes. Their unusual seismic signals make them a potential source of false alarms, but new algorithms have been developed that can distinguish such events from both explosion and earthquakes.

Unsuccessful Proposals for Clandestine Underground Nuclear-Explosion Testing

Several other scenarios have been proposed for clandestine underground testing, but none is considered likely to be successful:

- *Hiding signals of an explosion in that of an earthquake*—Modern instruments detect seismic waves from earthquakes and nuclear explosions over a very broad range of frequencies and at many different distances. Signals from small nuclear explosions can be separated from those of large earthquakes by simple filtering in the frequency domain, using arrays to separate signals arriving from different azimuths and wave speeds, and looking at data from regional stations closest to the presumed explosion. Because earthquakes cannot be predicted, a wait of years typically would be involved after emplacing a nuclear device and then determining in a very short amount of time that a large nearby earthquake had occurred.
- *Set off series of explosions so seismic waves look like those from an earthquake*—This idea was proposed about 40 years ago when identification was made using seismic waves with only two periods, about 1 and 20 seconds—the Ms/mb technique. This evasion proposal does not work when digital data are used, as they are today, with a broad range of periods.
- *Absorb energy by placing carbon in cavity containing an explosion*—very small U.S. tests of this concept many decades ago were not successful.
- *Reduce size of seismic waves by testing in rubble zone of a previous nuclear explosion*—Sites of past nuclear explosions that generated rubblized zones of any significant size are known and can be monitored. Rubblized zones are likely to be conduits for noble gases and other bomb-produced radionuclides.

Seismic waves from nuclear explosions in the Degelen Mountain subsite of the Semipalatinsk Test Site, Kazakhstan, reportedly were about ten times smaller than expected for an explosion conducted close to the underground location of an earlier nuclear test (results reported by Sokolova, 2008). This modest “decoupling” factor, which is comparable to testing, say, in dry alluvium and thus not large enough to represent a significant problem, should be explored by simulation and non-nuclear experiment.

APPENDIX F

Issues Related to Containment of Radioactivity

Monitoring communities have unfortunately used the terms “containment,” “venting,” and “seeping” in different ways. The formal use of these terms may originate from wording adopted in the United States and a “Containment Evaluation Panel” (CEP) that was established to review the containment of U.S. nuclear-explosion tests, though communities other than the past U.S. testing community may have different definitions of the terms. For example, the CEP (Carothers, 1995) defined *successful* containment as:

> *“Successful Containment: Containment such that a test results in no radioactivity detectable off site as measured by normal monitoring equipment and no unanticipated release of radioactivity on site within a 24 hour period following execution. Detection of noble gases which appear on site at long times after an event due to changing atmospheric conditions is not unanticipated. Anticipated releases will be designed to conform to specific guidance from DOE/DASMA (NV-176, Revision 5, Planning Directive for Underground Nuclear Tests at the Nevada Test Site (U))” (p. 7).*

During the time of active testing, it was in fact not unanticipated to have noble gases measurable on-site,[1] and “normal” offsite monitoring was far less sensitive than is today’s equipment. In addition, at the time, “late-time seepage” of noble gases was expected after operations ceased at the test site. Because the noble gasses are produced by radioactive decay of fission products produced in the explosion, the maximum amount of radioactive xenon actually occurs a few days after the shot time, and therefore seeps could be appreciable.

The definition used by the CEP is not particularly relevant for CTBT monitoring. First, for both IMS monitoring and NTM, the measurement technology is significantly advanced from even a decade ago. Second, if radioactivity is released at 24 hours, it would not be considered containment failure, though the IMS and NTM assets would still be usable for determination of a CTBT violation. Third, even though noble gases escaping from a nuclear test were not considered containment failure by the CEP, measurement of the radioactive noble gases is a key way to verify the CTBT.

Approximately 50 percent of all Soviet nuclear tests were measured off-site using noble-gas measurement technology (Dubasov et al., 1994). With the improvements of detection sensitivity, and in-field measurements, it is possible that the number of tests that would have been detectable off-site would be higher. Because of this, one might consider 50 percent as the limiting case for a mature nuclear weapon state with a lot of practice and somewhat lower for new proliferators. However, as the number of active scientists with experience with nuclear testing and nuclear test containment decreases, it is likely that the probability for successful containment of nuclear tests may end up lower because of the lost experience base, much of which is not documented.

Another data point is the U.S. experience with the trapping of radionuclides from underground nuclear testing. In reporting from the U.S. Department of Energy, from nuclear tests conducted between 1961 and 1992 on the release of radioactive debris into the atmosphere, of the 723 underground nuclear tests conducted during this period, 105 (14.5

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[1] Ward Hawkins, personal communication, 2009.

percent) had “containment failures,” 287 (39.7 percent) had operational releases, and 322 (44.5 percent) were “contained.”[2] This means that of the 427 nuclear tests since 1961 where no release was expected, approximately 25 percent did vent according to the conservative definition used by the CEP.

Because there is little detailed data available, it appears that the U.S. experience with containment of nuclear tests does not seem *radically* different than the Soviet containment experience. Therefore, as a rule of thumb, we judge that in at least 50 percent of nuclear tests near 1 kiloton or larger, even those carried out by experienced testers, xenon noble gases may be detectable offsite above the detection limits of the IMS (0.1 mBq/m^3) from prompt venting of nuclear tests; also, long-term seepage of appreciable noble gases would be expected that could be detectable, both offsite and onsite.

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[2] Of the 723 tests, 9 (1.2 percent) were either Plowshare or other late time releases (U.S. Department of Energy, 1996).

APPENDIX G[1]

U.S. Satellite Nuclear Detonation Detection Capability: Options and Impacts

This appendix includes information that illustrates the concerns described in Chapter 2 of the unclassified text regarding the future of the United States satellite nuclear detonation detection monitoring capabilities—in particular, the potential capabilities under various scenarios of future satellite systems. Missions of the U.S. Nuclear Detonation Detection System (USNDS) are to support treaty monitoring, warfighting, and space control. System requirements are set in various regions of the atmosphere and space, from the earth's surface through outer space, to meet mission requirements. Each mission comprises a subset of the USNDS functions: detect, identify, locate, estimate yield, and characterize.

The Air Force satellite constellations enabling the ability to meet the mission requirements are the Global Positioning System (GPS) and the geostationary Defense Support Program (DSP) satellites. The nuclear detonation detection sensor packages provided by DOE/NNSA are the NDS on GPS and the ARII (Advanced RADEC II) plus optical sensors on DSP.

Over the past decade, DOE/NNSA research and development investments have resulted in improved sensors for monitoring nuclear detonations in all environments which are responsive to USAEDS monitoring requirements for the CTBT. Air Force plans for upgrading GPS (Blocks II F and III) and for the replacement of the geostationary DSP—(with the Space-Based Infrared System, or SBIRS-D110)—are advancing, and may not take advantage of this improved nuclear detonation monitoring capability. The future of the nuclear-detonation detection sensors on GPS upgrades and DSP replacements is highly uncertain. For example, RADEC sensors are not included on at least the first two SBIRS satellites, and may not be included on any future SBIRS constellation. Similarly, exactly what nuclear detonation detection capability, if any, will be carried on future GPS Block III satellites remains uncertain. At the time of this writing, the Air Force has reportedly committed through a written memorandum of agreement with DOE/NNSA to carry enhanced NDS payloads on GPS Block II F and Block III satellites. If so, and the commitment is carried out, the GPS-enhanced nuclear-detonation detection capability, supportive of CTBT monitoring, will be sustained beyond 2020.

It is urgent that decisions regarding future nuclear detonation detection satellite capabilities be reviewed now.

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[1] The information presented here is adapted from a briefing received by the committee from DOE/NNSA NA-22 on September 30, 2009.

APPENDIX H

Satellite-Based Challenges and Solutions

Satellite-based monitoring is discussed in Chapter 2. Major advances in satellite sensors to detect nuclear explosions in the atmosphere or space have been made over the past decade. These advances are summarized in Table H-1 in the format of major technical challenges identified a decade ago and the technology solutions subsequently accomplished. They primarily result from investments by DOE/NNSA made at the national laboratories, responding to potentially new nuclear threats from transnational terrorists or nascent Nuclear Weapon States. Uncertainties regarding the actual employment of these new monitoring technologies on future satellite platforms are discussed in Chapter 2 and Appendix G.

TABLE H-1: Satellite-Based Monitoring Program Challenges and Technology Solutions.

Challenges	Technology Solutions
Program Element: Integration of New Assets	
Incorporate vastly increased data flows from new optical and electromagnetic pulse (EMP) sensors into existing system architecture.	Additional downlink capacity through either more ground sites or more storage and bandwidth Sophisticated on-board triggering algorithms Algorithms for ground processing Improved methods of processing/identifying non-nuclear events
Program Element: Advanced Event Characterization	
Increase the absolute sensitivity of sensors for detecting & locating atmospheric nuclear detonations	Focal-plane-array active-pixel technology (thousands of individual optical sensors implemented in a space not appreciably larger than that required for today's single optical sensor) New sensor technologies as integrated circuit technology improves
Provide multi-phenomenology sensing capabilities to increase confidence of identification and improve existing capabilities for characterizing nuclear detonations from space	Autonomous EMP sensors and associated techniques to distinguish RF generated by nuclear explosions from natural phenomena Neutron and gamma-ray sensors on new satellite platforms
Program Element: Next-Generation Monitoring Systems	
Reduce detection thresholds for satellite systems while maintaining low false-event alarms	Array-based optical sensors Wide-band RF systems Sophisticated real-time triggering algorithms
Reduce size, weight, and power required for monitoring systems	Advanced electronics and field-programmable gate arrays Multi-function sensors Advanced packaging technologies to allow more electronics integration

SOURCE: U.S. DOE, 2004

APPENDIX I

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APPENDIX J

List of Acronyms

AFTAC	Air Force Technical Applications Center
AoA	Analysis of Alternatives
ALCM	Air-Launched Cruise Missile
ASC	Advanced Simulation and Computing
ATM	Atmospheric Transport Modeling
AWE	Atomic Weapons Establishment
BAA	Broad Agency Announcement
CBM	Confidence-Building Measure
CEP	Containment Evaluation Panel
CFR	Code of Federal Regulations
CMR	Chemistry and Metallurgy Research
CMRR	Chemistry and Metallurgy Research Replacement Facility
CTBT	Comprehensive Nuclear Test Ban Treaty
CTBTO	Comprehensive Nuclear Test Ban Treaty Organization
DARHT	Dual-Axis Radiographic Hydrodynamic Test Facility
DAS	Deployable Analysis System
DOD	Department of Defense
DOE	Department of Energy
DNI	Director of National Intelligence
DP	Defense Programs
DSP	Defense Support Program
DSB	Defense Science Board
DTRA	Defense Threat Reduction Agency
ECM	Event Classification Matrix
EIF	Entry into Force
EMP	Electromagnetic Pulse
ESP	Enhanced Surveillance Program
FTE	Full-Time Equivalent
GCI	Global Communications Infrastructure
GNEM	Ground Nuclear Explosion Monitoring
GNEMRD	Ground Nuclear Explosion Monitoring Research and Development
GPS	Global Positioning System
GWACS	Ground Whole Air Collection System
HE	High Explosives
HEAF	High Explosives Applications Facility
HEMP	High Altitude Electromagnetic Pulse
HEU	Highly Enriched Uranium

HEUMF	Highly Enriched Uranium Materials Facility
ICBM	Intercontinental Ballistic Missile
ICF	Inertial Confinement Fusion
IDC	International Data Centre
IFE	Integrated Field Exercise
IMS	International Monitoring System
INGE	International Noble Gas Experiment
ISC	International Seismological Center
IRIS	Incorporated Research Institution for Seismology
JASPER	Joint Actinide Shock Physics Experimental Research Facility
kt	Kiloton
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LEP	Life-Extension Program
LLNL	Lawrence Livermore National Laboratory
MASINT	Measurement and Signature Intelligence
m_b	Body Wave Magnitude
MESA	Microsystems and Engineering Sciences Application Facility
MJ	Megajoule
MOD	Ministry of Defence (UK)
MSS	Mass Storage System
NDC&A	Nuclear Debris Collection and Analysis System
NEP	Nuclear Explosive Package
NEIC	National Earthquake Information Center
NEPA	National Environmental Policy Act
NIC	National Ignition Campaign
NIE	National Intelligence Estimate
NIF	National Ignition Facility
NNSA	National Nuclear Security Agency
NPT	Nuclear Non-Proliferation Treaty
NPR	Nuclear Posture Review
NRC	National Research Council
NTM	National Technical Means
NTS	Nevada Test Site
NWS	Nuclear Weapon States
OSI	On-Site Inspection
PAS	Portable Air Sampler
PTS	Provisional Technical Secretariat
QMU	Quantification of Margins and Uncertainties
REB	Reviewed Event Bulletin
RREB	Reviewed Radionuclide Event Bulletin

RNEP	Robust Nuclear Earth Penetrator
RRB	Report Radionuclide Bulletin
RRW	Reliable Replacement Warhead
SBIRS	Space-Based Infrared System
SLBM	Submarine-Launched Ballistic Missile
SLCM	Submarine-Launched Cruise Missile
SNL	Sandia National Laboratories
SOFAR	Sound Fixing and Ranging
SORT	Strategic Offensive Reduction Treaty
SRS	Savannah River Site
SSP	Stockpile Stewardship Program
STP	Surveillance Transformation Project
STRATCOM	U.S. Strategic Command
UPF	Uranium Processing Facility
USAEDS	United States Atomic Energy Detection System
USGS	United States Geological Survey
USNDC	United States National Data Center

APPENDIX K

Glossary of Key Terms from the 2010 CTBT NIE

For the convenience of the reader and for purposes of comparison with this report, we have provided some definitions of key terms from the 2010 CTBT National Intelligence Estimate (CTBT NIE, 2010). Drawing from the CTBT NIE and its own knowledge, the committee has also provided definitions of nuclear weapon classes.

Understanding Key Terms in This Estimate

Nuclear test monitoring refers to the persistent global surveillance of underwater underground, atmospheric, and space environments for nuclear explosions. The scientific and monitoring communities do not use the terminology describing technical monitoring tasks consistently, making it necessary to take extra care when comparing findings between different organizations. In this Estimate, we use the following definitions.

Detection is the determination that an event of interest has occurred at a given location. Detection alone does not indicate whether an event was an explosion or if so, whether it was nuclear.

Identification is the determination that an event was an explosion. During the identification process, data are screened to discriminate among natural events, explosive events, and indeterminate events. Identification alone does not determine whether an event is nuclear.

Characterization is the determination that an explosion was nuclear in nature as determined by the collection of nuclear explosion debris or detection of unique signatures by satellite.

Attribution is the determination of the state or actor responsible for a nuclear explosion.

The ***threshold*** is the minimum yield at which a statistically significant percentage of all events can be detected, identified, or characterized, with technical monitoring systems.

By ***high confidence*** we mean detecting, identifying, or characterizing at least 90 percent of the events with yields above a certain threshold.

In a ***fully coupled*** underground nuclear test, the explosive energy fully interacts with the surrounding medium (e.g., rock or water), maximizing the seismic waves detected by our networks.

Nuclear Weapon Classes

A ***nuclear warhead or bomb*** is a nuclear explosive device that has been weaponized for delivery.

A ***fission device*** is a supercritical assembly of fissile material that disassembles explosively. The fission reactions produce the nuclear explosive yield of the device.

A ***boosted-fission device*** uses a fission explosion to cause a small amount of deuterium and tritium gas to undergo nuclear fusion. This fusion produces energy and extra neutrons that cause more fissions in the fissile material, which results in a greater explosive yield and a more efficient use of the fissile material. The amount of fusion yield produced in a boosted-fission device is a small fraction of the weapon's total yield, but the fusion "boosts" the fission yield.

A ***thermonuclear device*** uses a fission or boosted-fission device as a "primary stage" that produces the energy required to implode a separate "secondary stage." The secondary stage uses both fusion and fission reactions to generate nuclear explosive yield.

A ***neutron bomb*** is a weapon designed to increase lethality to personnel and ballistic missile warheads by increasing the weapon's output of higher energy neutrons.

An ***electromagnetic pulse (EMP) weapon*** is designed to create strong electromagnetic fields through the interaction of gamma rays with the ions in the atmosphere and any conducting materials with which the radiation comes in contact.