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North Korea's 2009 Nuclear Test: Containment, Monitoring, Implications

Jonathan Medalia
Specialist in Nuclear Weapons Policy

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Summary

On May 25, 2009, North Korea announced that it had conducted its second underground nuclear test. Unlike its first test, in 2006, there is no public record that the second one released radioactive materials indicative of a nuclear explosion. How could North Korea have contained these materials from the May 2009 event and what are the implications?

As background, the Comprehensive Nuclear-Test-Ban Treaty (CTBT) would ban all nuclear explosions. It was opened for signature in 1996. Entry into force requires ratification by 44 states specified in the treaty, including the United States and North Korea. As of November 2010, 153 states, including 35 of the 44, had ratified. North Korea has not signed the CTBT. President Clinton signed it in 1996; in 1999, the Senate voted not to consent to its ratification. In 2009, President Obama pledged to press for its ratification.

The treaty establishes a verification mechanism, including an International Monitoring System (IMS) to detect nuclear tests. Three IMS technologies detect waves that pass through the oceans (hydroacoustic), Earth (seismic), or atmosphere (infrasound); a fourth detects radioactive material from a nuclear test. Scientists concur that only the latter proves that an explosion was nuclear. Some believe that deep burial and other means can contain radioactive effluents. Another view is that containment is an art as much as a science. The United States learned to improve containment over several decades. Yet by one estimate, North Korea contained over 99.9% of the radioactive effluents from its 2009 test. It might have done so by application of lessons learned from its 2006 test or the U.S. nuclear test experience, use of a higher-yield device, release of material below the detection threshold, good luck, or some combination. Alternatively, the 2009 event may have been a nonnuclear explosion designed to simulate a nuclear test.

Containment could be of value to North Korea. It could keep radioactive fallout from China, Japan, Russia, or South Korea, averting an irritant in relations with them. It could prevent intelligence services from gathering material that could reveal information about the weapon that was tested. It could permit North Korea to host nuclear tests by other nations, such as Iran; while such tests would be detected by seismic means, they could not be attributed to another nation using technical forensic means if effluents, especially particles, were contained.

An issue for Congress is how containment could affect CTBT prospects. Supporters might argue that explosion-like seismic signals without detected radioactive material would lead to calls for an onsite inspection. Opponents might claim that only detection of radioactive material proves that a nuclear explosion occurred. Both would note inspections could not be required unless the treaty entered into force, supporters to point to a benefit of the treaty and opponents to note that North Korea could block inspections by not ratifying the treaty. Congress may wish to consider ways to improve monitoring capability, such as supporting further research on test signatures, improving monitoring system capability, and deploying more monitoring equipment. This update reflects developments in the North Korean uranium program and prospects for another nuclear test.

Related CRS reports include CRS Report RL34256, *North Korea's Nuclear Weapons: Technical Issues*, which summarizes open-source information on that nation's nuclear weapons program, including fissile material and warhead estimates, and assesses developments toward denuclearization; and CRS Report R40684, *North Korea's Second Nuclear Test: Implications of U.N. Security Council Resolution 1874*, which analyzes possible economic effects on North Korea of sanctions and vessel inspections that Resolution 1874 puts in place.

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Background

On May 25, 2009, North Korea announced that it had conducted a nuclear test.[1] The test produced seismic signals characteristic of an explosion, indicating that they were generated by human activity. They were detected by at least 61 seismic stations. However, no radioactive materials were reportedly detected, in contrast to the first North Korean test on October 9, 2006. Such materials could confirm that the test was nuclear. Although a sample size of one is not sufficient to draw conclusions with high confidence, the possible ability of North Korea to contain radioactive materials from a nuclear test could be of value for that nation. This report presents what is known publicly about the tests, discusses detection and containment of nuclear tests, explores the possible significance of containment for North Korea, and raises, as issues for Congress, implications for the Comprehensive Nuclear-Test-Ban Treaty (CTBT) and possible means of improving U.S. and international ability to monitor nuclear testing.

States currently possessing nuclear weapons would probably need to conduct nuclear tests to develop more advanced designs and, some argue, to ensure that existing weapons are safe, secure, and reliable. States with fledgling nuclear weapon programs could design and deploy the simplest type of nuclear weapon without testing,[2] but such weapons make very inefficient use of scarce fissile material and are heavy and bulky. To develop small, rugged, powerful warheads for long-range missiles, these states would need to conduct nuclear tests.

Nonnuclear experiments can answer some questions important to the design of nuclear weapons, but many processes essential to the functioning of a nuclear weapon can only be studied under the conditions of an actual nuclear test. Each test not only shows whether a device "works" or "fails," but also provides much more data. Many technical disciplines contribute to a test, and each gains data from it. Weapon designers learn how the design might be improved, physicists gain data on the science underlying nuclear explosions, metallurgists gain data on how uranium or plutonium deforms under pressure, engineers can discover unanticipated flaws arising from manufacturing processes, physicists who design computer models of nuclear weapon performance gain data to refine their models, electrical engineers gain data to improve the instrumentation for collecting nuclear test data, radiochemists can analyze radioactive samples from the test for data on the yield and performance of the device, and those involved in preventing radioactive material from escaping from the test gain data to improve containment.

Because testing is crucial for developing weapons, efforts to ban nuclear tests have been underway for decades as an arms control measure.[3] The multilateral 1963 Limited Test Ban Treaty banned atmospheric, space, and underwater tests. The U.S.-Soviet Threshold Test Ban Treaty and Peaceful Nuclear Explosions Treaty, signed in 1974 and 1976, respectively, limited underground nuclear explosions to a yield of 150 kilotons.[4] Both entered into force in 1990.

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[1] "Text of the North Korean Announcement of Nuclear Test," *Reuters*, May 25, 2009, http://www.nytimes.com/2009/05/25/world/asia/25nuke-text.html. For information on North Korea's nuclear weapons program, see CRS Report RL34256, *North Korea's Nuclear Weapons: Technical Issues*, by Mary Beth Nikitin.

[2] In a "gun assembly" weapon, one piece of uranium-235 is fired into another such piece to create a critical mass. The Hiroshima bomb was of this design. U.S. scientists had such confidence in this design that they did not test it prior to use. Gun-assembly weapons can only use highly enriched uranium, not plutonium.

[3] For a history of nuclear test bans, see Appendix A in CRS Report RL34394, *Comprehensive Nuclear-Test-Ban Treaty: Issues and Arguments*, by Jonathan Medalia.

[4] One kiloton is equivalent to the explosive force of 1,000 tons of TNT. For comparison, the explosive yield of the (continued...)

In an attempt to extend these bans to cover all nuclear tests, negotiations on the CTBT were completed in 1996. The treaty's basic obligation is to ban all nuclear explosions. It establishes an International Monitoring System (IMS) to monitor signs of an explosion. The treaty contains procedures for authorizing and conducting on-site inspections (OSIs), which would search the site of a suspected nuclear test for evidence of the test, and permits data from national technical means of verification as well as from the IMS to be used to support a request for an OSI.

As of November 2010, 182 nations had signed the treaty and 153 of them had ratified.[5] To enter into force, 44 specified nations, basically those with a nuclear reactor in 1995 or 1996, must all ratify. As of November 2010, 35 had done so; the others are China, Egypt, India, Indonesia, Iran, Israel, North Korea (the Democratic People's Republic of Korea, DPRK), Pakistan, and the United States. The U.S. Senate voted not to give its advice and consent to ratification of the treaty, 48 for, 51 against, and 1 present, in 1999. Two uncertainties that led to its defeat concerned U.S. ability to verify compliance with the treaty and U.S. ability to maintain its nuclear stockpile without testing. In April 2009, President Obama pledged to pursue U.S. ratification of the CTBT "immediately and aggressively."[6]

The North Korean Nuclear Tests

The 2006 Test

North Korea conducted its first nuclear test on October 9, 2006. It was clearly nuclear because it released radioactive materials. The U.S. Office of the Director of National Intelligence (ODNI) released this 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."[7] (ODNI declined to state whether "debris" referred to particulates, gases, or both.[8]) According to a press report, "American intelligence agencies have concluded that North Korea's test explosion last week was powered by plutonium that North Korea harvested from its small nuclear reactor, according to officials who have reviewed the results of atmospheric sampling since the blast."[9] In a similar vein, the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Preparatory Commission (PrepCom) stated, "Two weeks after the event, the radionuclide noble gas station at Yellowknife, Canada, registered a higher concentration of Xenon 133. Applying atmospheric transport models to backtrack the dispersion of the gas, its registration at Yellowknife was found

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Hiroshima bomb was 15 kilotons.

5 For the status of signatures and ratifications, and text of the treaty, see the website of the Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, http://www.ctbto.org. For current developments on the CTBT, see CRS Report RL33548, *Comprehensive Nuclear-Test-Ban Treaty: Background and Current Developments*, by Jonathan Medalia.

6 U.S. White House. Office of the Press Secretary. "Remarks by President Barack Obama," Hradcany Square, Prague, Czech Republic, April 5, 2009, http://www.whitehouse.gov/the_press_office/Remarks-By-President-Barack-Obama-In-Prague-As-Delivered/.

7 U.S. Office of the Director of National Intelligence. Public Affairs Office. "Statement by the Office of the Director of National Intelligence on the North Korean Nuclear Test," news release 19-06, October 16, 2006.

8 Information provided by Office of the Director of National Intelligence, personal communication, July 17, 2009.

9 Thom Shanker and David Sanger, "North Korean Fuel Identified as Plutonium," *New York Times*, October 17, 2006.

to be consistent with a hypothesized release from the event in the DPRK."[10] The Swedish Defence Research Agency (FOI) used atmospheric models at a much shorter distance. It flew mobile xenon analysis equipment to South Korea and began collecting samples within three days of the test. "All the samples were found to contain radioactive xenon and, in combination with meteorological information, FOI were able to conclude that the gas did, with a relatively high level of probability, originate from the area in North Korea where the explosion took place."[11]

The 2009 Test

North Korea announced on May 25, 2009, that it had conducted a second nuclear test. ODNI stated: "The U.S. Intelligence Community assesses that North Korea probably conducted an underground nuclear explosion in the vicinity of P'unggye on May 25, 2009. The explosion yield was approximately a few kilotons. Analysis of the event continues."[12] The lack of certainty as to whether the test was nuclear arises because seismic signals, including those detected by 61 stations of the IMS,[13] were consistent with a nuclear test, and seismic signals from the 2006 and 2009 events were very similar,[14] but open sources did not report the detection of physical evidence that would provide conclusive proof of a nuclear test, such as certain radioactive isotopes of noble gases or radioactive particulates (i.e., fallout). For example, the CTBTO PrepCom stated,

> The detection of radioactive noble gas, in particular xenon, could serve to corroborate the seismic findings. Contrary to the 2006 announced DPRK nuclear test, none of the CTBTO's noble gas stations have detected xenon isotopes in a characteristic way that could be attributed to the [2009] DPRK event so far, even though the system is working well and the network's density in the region is considerably higher than in 2006. …
>
> Nor have CTBTO Member States using their own national technical means reported any such measurements. Given the relatively short half-life of radioactive xenon (between 8 hours and 11 days, depending on the isotope), it is unlikely that the IMS will detect or identify xenon from this event after several weeks.[15]

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[10] Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, "The CTBT Verification Regime Put to the Test – The Event in the DPRK on 9 October 2006," http://www.ctbto.org/press-centre/highlights/2007/the-ctbt-verification-regime-put-to-the-test-the-event-in-the-dprk-on-9-october-2006/page-2/. An atmospheric transport model, as discussed later, shows how winds move gases or particles through the atmosphere. Xenon is a noble gas, i.e., one that is chemically inert. Nuclear explosions create radioactive isotopes of some noble gases. The IMS has some stations that can detect radioactive isotopes of xenon, such as xenon-133.

[11] Swedish Defence Research Agency (FOI), "FOI found radioactive xenon following explosion in North Korea," press release, December 19, 2006, http://www.foa.se/FOI/Templates/NewsPage____5412.aspx.

[12] U.S. Office of the Director of National Intelligence. Public Affairs Office. "Statement by the Office of the Director of National Intelligence on North Korea's Declared Nuclear Test on May 25, 2009," ODNI News Release No. 23-09, June 15, 2009, http://www.dni.gov/press_releases/20090615_release.pdf.

[13] Comprehensive Nuclear-Test-Ban Treaty Preparatory Commission, "Homing in on the Event," May 29, 2009, http://www.ctbto.org/press-centre/highlights/2009/homing-in-on-the-event/.

[14] For seismograms of these two events and of an earthquake from the same region, see Won-Young Kim, Paul Richards, and Lynn Sykes, "Discrimination of Earthquakes and Explosions Near Nuclear Test Sites Using Regional High-Frequency Data," poster SEISMO-27J presented at the International Scientific Studies Conference, June 2009, http://www.ctbto.org/fileadmin/user_upload/ISS_2009/Poster/SEISMO-27J%20%28US%29%20-%20Won_Young_Kim%20_Paul_Richards%20and%20Lynn_Sykes.pdf.

[15] Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, "Experts Sure about the Nature of the DPRK Event," (referring to the May 2009 North Korean test), June 12, 2009, http://www.ctbto.org/press-centre/
(continued...)

It would be desirable to establish if the event was nuclear because the possibility that chemical explosives caused the seismic waves could undermine confidence in the ability to verify compliance with the CTBT. Earthquakes can be differentiated from explosions (whether chemical or nuclear) because their seismic waves have different characteristics. But while seismic signals from the 2009 event were consistent with a nuclear test, it is very difficult to differentiate between seismic signals generated by a nuclear test and a chemical explosion of comparable energy, so it is conceivable that the test was nonnuclear. Geoffrey Forden, a scientist at MIT, posits a scenario in which a room could be filled with 2,500 tons of TNT, enough to create an explosion within the yield range estimated for the 2009 North Korean test, in two months using about four 10-ton truckloads per day. He finds this scenario "quite doable and to be potentially undetectable by the West."[16] The United States conducted large aboveground[17] and underground[18] tests using chemical explosives to simulate some effects of nuclear explosions.

The CTBTO PrepCom cites analysis that rejects the chemical-explosive possibility:

> Verification technology experts such as Professor Paul Richards from the Lamont-Doherty Earth Observatory, Columbia University, USA, considered the scenario of a "bluff", i.e. the creation of a nuclear explosion-like seismic signal using conventional explosives. While technically possible, he stated that it was highly implausible. As CTBTO seismic data have clearly indicated an explosion of a yield many times greater than that of 2006, it would have required several thousand tons of conventional explosives to be fired instantaneously. Richards explained that such a massive logistical undertaking would have been virtually impossible under the prevailing circumstances and would not have escaped detection.[19]

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highlights/2009/experts-sure-about-nature-of-the-dprk-event/.

[16] Geoffrey Forden, "DPRK: Drilling for Nuke Verification," *Arms Control Wonk*, July 20, 2009, http://www.armscontrolwonk.com/2392/dprk-nuke-verification-will-require-drilling.

The amount of chemical explosive needed to implement this scenario may be less than it would appear. For example, one study observes a range of calculations in which it takes a nuclear explosive with a yield of 1 to 2 kilotons to produce the seismic signature of 1 kiloton of chemical explosive. That study calculates that 1.25 kilotons of nuclear explosives produces the seismic signature of 1 kiloton of chemical explosive. James Kamm and Randy Bos, "Comparison of Chemical and Nuclear Explosions: Numerical Simulations of the Non-Proliferation Experiment," Los Alamos National Laboratory report LA-12942-MS, UC-700 and UC-703, June 1995, pp. 89-92, http://www.osti.gov/bridge/servlets/purl/72900-YlaqIV/webviewable/72900.pdf. Another study finds, "The basic results from the U.S. Department of Energy's (DOE's) Non-Proliferation Experiment (NPE) for seismic signal generation are that the source function for a chemical explosion is equivalent to that of a nuclear explosion of about twice the yield.…" Marvin Denny et al., "Seismic Results from DOE's Non-Proliferation Experiment: A Comparison of Chemical and Nuclear Explosions," Lawrence Livermore National Laboratory, UCRL-JC-119214 preprint, January 1995, p. 1, http://www.osti.gov/energycitations/servlets/purl/93630-EAQRwr/webviewable/93630.pdf. (The NPE was an underground nonnuclear explosion of about 1 kiloton yield conducted in 1993 to simulate a nuclear explosion.)

[17] In 1985, the Defense Nuclear Agency conducted a test, "Minor Scale," using 4,800 tons of high explosive. U.S. Department of Defense. Defense Threat Reduction Agency. *Defense's Nuclear Agency, 1947-1997*, Washington, 2002, pp. 269-270.

[18] See "Nonproliferation, Arms Control, and International Security," Lawrence Livermore National Laboratory, c. 1995, p. 8, https://www.llnl.gov/etr/pdfs/01_95.02.pdf; and "Non-Proliferation Experiment (NPE)," Globalsecurity.org, http://www.globalsecurity.org/wmd/ops/npe.htm.

[19] Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, "Experts Sure about the Nature of the DPRK Event."

Specifically, satellite imagery might have detected preparations for a large chemical explosion, and if the explosives did not detonate instantaneously, they could have caused a seismic signal with characteristics of a chemical explosion.[20]

Questions about whether the May 25 event was nuclear or nonnuclear remain unresolved. Onsite inspections could prove conclusively that a test was nuclear, but they could only be conducted if the CTBT were to enter into force, or if North Korea gave its permission outside the treaty. Other ways to establish (but not necessarily prove) that an explosion was nuclear are nonseismic means, such as communications intercepts and satellite imagery; note that high-quality commercial satellite imagery is available for purchase. The CTBT envisions that some monitoring technologies not part of the IMS could be added (Article IV, paragraphs 11, 23) to that system if agreed pursuant to the treaty's amendment process (Article VII).

The apparent absence of radioactive material released from the May 25 event raises several questions: How can such material be detected? How might North Korea have contained its second test? What are some implications of successful containment for North Korea? What issues do detection and containment raise for Congress? This report now turns to these questions.

Monitoring and Containing Nuclear Tests

Monitoring, Verification, Intelligence

Central concerns in negotiating an arms control agreement are to establish a regime that facilitates detection of cheating and to ensure, insofar as possible, that a state party to the treaty cannot gain an advantage by cheating. To this end, the CTBT, the CTBTO, and individual nations would take several interlocking steps. The first is monitoring, which provides technical data on suspicious events. The treaty establishes the IMS, which is one of several components in the verification regime established by Article IV of the treaty. Verification refers to determining whether a nation is in compliance with its treaty obligations, which in this case means determining whether a suspicious event was a nuclear test. The treaty establishes the verification regime in great detail: Article IV takes up nearly half the treaty, and the Protocol, which provides details on the verification regime, is nearly as long as the treaty itself. The verification regime, in addition to the IMS, includes provisions for consultation and clarification of suspicious events; an International Data Center (IDC) to analyze IMS data and distribute the results to states parties to the treaty; detailed provisions for on-site inspections; and confidence-building measures. As one of its functions, the Provisional Technical Secretariat of the CTBTO PrepCom operates the verification regime.[21]

[20] A large chemical explosion designed to mimic a nuclear explosion but that is not detonated all at once could generate signals that can be differentiated from a nuclear explosion. Similarly, mining explosions are often ripple-fired and, as a result, generate a different seismic signal than would a nuclear explosion.

[21] The CTBTO and Technical Secretariat would come into existence only upon entry into force of the CTBT. As an interim measure, the states that had signed the CTBT in 1996 adopted a resolution establishing the CTBTO Preparatory Commission as a means "to ensure the rapid and effective establishment of the future Comprehensive Nuclear-Test-Ban Treaty Organization." "Resolution Establishing the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization," adopted November 19, 1996, U.N. document CTBT/MSS/RES/1. Upon entry into force of the CTBT, the CTBTO Preparatory Commission would become the CTBTO and the Provisional Technical Secretariat would become the Technical Secretariat.

The treaty (Article IV, paragraph 14) does not direct the Technical Secretariat to determine that a particular nation has cheated. But while some IMS sensors (e.g., seismic) can only provide evidence that a nuclear test may have occurred, IMS radionuclide sensors would prove that a nuclear test had occurred if they found certain types of radioactive debris, and an OSI would prove that a nuclear test had occurred at a particular location if it found the radioactive cavity left by an underground nuclear test. Once the verification regime provides data and analysis of suspected or actual nuclear tests to the states parties, the role of the Technical Secretariat would end. In the event of a suspected violation, the Conference of the States Parties, pursuant to Article V, paragraphs 3 and 4, "may recommend to States Parties collective measures which are in conformity with international law," or the conference or the Executive Council "may bring the issue … to the attention of the United Nations."[22]

In judging how to respond, nations would use various means to determine whether the event was a nuclear test, combining data and analysis from multiple sources, such as the International Data Center; national technical means of verification; non-technical means, such as information from people and open sources; and other governments and nongovernmental organizations. But because of background noise, limitations of detectors, etc., it is almost a truism that there will always be some threshold below which a nuclear test cannot be unambiguously identified by seismic and other IMS technologies. As a result, a decision on a nation's response to a suspected nuclear test would depend not on perfect verification but on effective verification. In 1988, Paul Nitze offered a widely-used definition: by effective verification, "[w]e mean that we want to be sure that, if the other side moves beyond the limits of the treaty in any militarily significant way, we would be able to detect such violation in time to respond effectively, and thereby deny the other side the benefit of the violation."[23] Judgments on the effectiveness of verification have been crucial in consideration of past nuclear testing treaties; this is likely to be the case for any future CTBT debate as well.

Beyond that, some nations can be expected to use their intelligence capabilities to learn more than whether an event was a nuclear test. They will want to know such details as weapon yield, weapon fuel (uranium or plutonium), and weapon design to understand how quickly a nation's weapons program is advancing, what problems it is encountering, and what development path it is following. In some cases, such as a nuclear detonation in a remote ocean area or by terrorists, technical analysis may support attribution of the detonation to a specific nation.

Monitoring Nuclear Tests

Because a nuclear test generates immense amounts of energy and radioactive material, it presents many signatures by which it can be detected, some at a distance of thousands of miles, others only on site. Atmospheric tests are easy to detect because of their radioactive fallout. China conducted the most recent atmospheric nuclear test in October 1980.[24] Underwater tests are also easy to detect, though attribution may be a problem. Satellites (not part of the IMS) can detect nuclear tests in space, though some evasion scenarios have been suggested. A particularly

[22] Pursuant to Article II of the treaty, the Conference of the States Parties is composed of all states that are parties to the treaty. The Executive Council has 51 member states and is the executive organ of the CTBTO.

[23] U.S. Congress. Senate. Committee on Foreign Relations. *The INF Treaty.* S.Hrg. 100-522, 100th Congress, 2nd Session, 1988, part 1, p. 289.

[24] Nuclear Threat Initiative, "China's Nuclear Tests: Dates, Yields, Types, Methods, and Comments," http://www.nti.org/db/china/testlist.htm.

difficult environment in which to detect clandestine tests is underground, and is the one relevant to North Korean nuclear testing, since both of its tests were conducted in that manner.

When completed,[25] the IMS will have 321 monitoring stations, 16 laboratories, and an International Data Center to process data. A Global Communications Infrastructure will link IMS facilities, the data center, and member states. As of November 2010, 248 monitoring stations and 10 laboratories were operational.[26] The IMS uses four technologies to detect nuclear tests:[27]

Seismic: Seismographs detect various types of waves (e.g., pressure waves) moving through the Earth.[28] The science of seismology has made great progress over the last half-century in filtering out seismic signals characteristic of explosions from other seismic signals, such as by using more sensitive instruments and more elaborate data-processing algorithms. However, there are some scenarios for concealing the seismic signals from low-yield tests that have been hotly debated for many years, as discussed later. Analysis of seismic and other waves cannot by itself prove that an explosion was nuclear; for example, it is difficult if not impossible to distinguish by seismic means between a nuclear explosion and a large (e.g., 1,000-ton) chemical explosion that is designed to mimic a nuclear explosion and is successfully conducted.

Hydroacoustic: Hydrophones can detect a very small underwater chemical explosion at distances of thousands of miles as pressure waves generated by the explosion move through the water, so an underwater nuclear explosion would be readily detected.[29] While this method might detect some nuclear tests conducted on land, such as on a small island, there were no reports that it was of use in detecting the 2009 North Korean test.

Infrasound: Sensors measure very small changes in atmospheric pressure caused by very low frequency acoustic waves. Infrasound sensors are not at present intended for monitoring of underground nuclear explosions, though they did detect the 2009 North Korean test.[30] The observed magnitude of the infrasound signal, approximately three tons of TNT equivalent[31] vs. several kilotons for the seismic signal,[32] indicated the explosion was not at the Earth's surface.[33]

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[25] While the IMS is to be completed by the time the CTBT enters into force, it could be completed sooner. CTBTO PrepCom believes it can project 90% completion, but the remainder depends on political, financial, and environmental factors. The support from Member States and countries hosting stations is necessary for completing the IMS. Information provided by Comprehensive Nuclear-Test-Ban Treaty Preparatory Commission, March 3, 2010.

[26] For an up-to-date list of these facilities, see http://www.ctbto.org/map/#ims.

[27] For details on the IMS, see http://www.ctbto.org/verification-regime/.

[28] The instrument that records seismic signals is a "seismograph" or "seismometer"; the visual record of these signals is a "seismogram." For an old but useful description of the science of seismic detection, see U.S. Congress, Office of Technology Assessment, *Seismic Verification of Nuclear Testing Treaties,* OTA-ISC-361, 139 pages, 1988, http://www.fas.org/ota/reports/8838.pdf.

[29] For example, IMS hydrophones near the coast of Chile detected signals from an underwater detonation of 20 kilograms of TNT, a tiny fraction of the yield of a nuclear weapon, off the coast of Japan, 16,300 km away. International Scientific Studies Conference (summary brochure), Vienna, Austria, June 10-12, 2009, p. 3, http://www.ctbto.org/fileadmin/user_upload/pdf/ISSAFC2_Web.pdf.

[30] Il-Young Che et al., "Infrasound Observation of the Apparent North Korean Nuclear Test of 25 May 2009," Geophysical Research Letters, vol. 36, L22802, doi: 10.1029/2009GL041017, 2009, 5 p.

[31] Ibid.

[32] Vitaly Fedchenko, "North Korea's Nuclear Test Explosion, 2009," Stockholm International Peace Research Institute (SIPRI) fact sheet, December 2009, pp. 3-4, http://books.sipri.org/files/FS/SIPRIFS0912.pdf.

[33] The difference in apparent magnitude (or yield) of the infrasound and seismic signals results from the great difference in density and compressibility between air and rock. Because the Earth is so stiff, even the relatively high (continued...)

Radionuclides: To gain direct physical evidence that an explosion was nuclear, the IMS monitors for radioactive particles and gases. When complete, it will have 80 stations that can detect radioactive particulates, of which 40 will also have equipment to detect radioactive forms of xenon, which are of particular value for detecting a nuclear explosion. The resulting data are sent to the IDC and national data centers for analysis. As of November 2010, 59 particulate stations, of which 25 had radioxenon collection capability, were operational.

Many technological advances made in recent years improve the ability to detect nuclear explosions. These include techniques to image the Earth's inner structure to better understand how that structure affects seismic waves,[34] use of satellite-borne "radar imaging technology to detect near-vertical surface deformations measuring less than 1 centimeter caused by underground disturbances,"[35] development of equipment to detect extremely low levels of radioactive noble gases,[36] development of computer models of wind patterns, use of seismic waves detected at regional as well as longer distances to improve the ability to discriminate between earthquakes and explosions,[37] and the rollout of the IMS.[38]

To resolve uncertainties over whether suspicious events—such as any that generate explosion-like seismic signals but do not release radioactive material—are nuclear, the CTBT provides for onsite inspections (OSIs). OSIs would search for signatures that can only be detected at a test site, such as small amounts of several radioactive noble gases, certain non-gaseous radioactive materials,[39] physical signs of a test (e.g., melted snow, changes to vegetation, pebbles thrown in bushes by ground shock), and the underground cavity formed by a nuclear test (found by drilling) that would have tell-tale radioactive debris. The treaty and its Protocol include great detail on authorization and conduct of an inspection. Article IV (verification), paragraph 56, of the treaty requires each state party to permit OSIs.[40] Of course, OSIs pursuant to the treaty could only occur after the treaty had entered into force, though it is possible that OSIs could be done outside the treaty regime, such as if requested by one country before the treaty enters into force to prove that it had not conducted a nuclear test, or pursuant to a bilateral agreement permitting one state to monitor another state's nuclear test site.

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pressure caused by an underground nuclear explosion moves the surface only a little, while air is so compressible that the small upward motion of the Earth's surface caused by the explosion generates only a small atmospheric pressure wave. Information provided by Raymond Jeanloz, Professor of Earth and Planetary Sciences, University of California, Berkeley, e-mail, January 5, 2010.

[34] Katie Walter, "Sleuthing Seismic Signals," *Science & Technology Review*, March 2009, pp. 4-12.

[35] Gabriele Rennie, "Monitoring Earth's Subsurface from Space," *Science & Technology Review*, April 2005, p. 5.

[36] Paul R.J. Saey, "Ultra-Low-Level Measurements of Argon, Krypton and Radioxenon for Treaty Verification Purposes," *ESARDA Bulletin*, no. 36 (July 2007), pp. 42-56.

[37] David Hafemeister, "Progress in CTBT Monitoring Since Its 1999 Senate Defeat," Science and Global Security, vol. 15 (2007), pp. 159-160.

[38] For 236 scientific posters from 2009 detailing various aspects of the IMS and technologies for monitoring nuclear explosions, see International Scientific Studies, "Scientific Contributions," http://www.ctbto.org/specials/the-international-scientific-studies-project-iss/scientific-contribtutions/.

[39] See James Ely et al., "Estimation of Ground-Level Radioisotope Distributions for Underground Nuclear Test Leakage," poster, International Scientific Study, http://www.ctbto.org/fileadmin/user_upload/ISS_2009/Poster/OSI-17B%20%28US%29%20-%20James_Ely%20etal.pdf.

[40] If a state party to the treaty refused to permit an OSI, Article V ("Measures to redress a situation and to ensure compliance, including sanctions") would presumably come into play. It provides for actions to "redress a situation," including collective measures and bringing the matter to the attention of the United Nations.

The United States has its own technical means of detecting nuclear explosions, which the Air Force Technical Applications Center (AFTAC) operates. AFTAC "operates and maintains a global network of nuclear event detection sensors called the U.S. Atomic Energy Detection System. Once the USAEDS senses a disturbance underground, underwater, in the atmosphere or in space, the event is analyzed for nuclear identification and findings are reported to national command authorities through Headquarters U.S. Air Force."[41] USAEDS predates the CTBT, and in the course of negotiations for that treaty, some USAEDS monitoring stations were included as contributing stations to the IMS. Similarly, in addition to performing independent analyses of events as the operator of USAEDS, AFTAC has a formal role under the CTBT as the U.S. National Data Center to receive data from the International Data Center.

What Radioactive Materials Can a Nuclear Test Release into the Atmosphere and How Can They Be Detected at a Distance?

An underground nuclear test may be fully contained, or it may release two types of material, particulates and gases, into the atmosphere. Either may prove that a nuclear test occurred. Gases include radioactive isotopes of noble gases (gases that are chemically inert), such as krypton-85, argon-37, and several xenon isotopes.

Krypton-85 is of little value for nuclear detection at a distance because a substantial background of this isotope is present in the atmosphere. Most of it is generated by nuclear power plants and is released when the spent fuel is reprocessed, but since its half-life is 10.76 years, some remains from past atmospheric nuclear tests.[42]

Argon-37 (half-life 35.04 days) is of value for onsite inspections and is not—but perhaps could be—used for long-range detection. It is produced when neutrons interact with calcium-40 in soil or rock.[43] While naturally-occurring neutrons produce a background of argon-37,[44] that mechanism would not produce a local concentration of the isotope. Therefore, finding a local concentration of it at the site of a suspected underground nuclear explosion would be an indicator of a nuclear explosion, making it of value for OSIs; one source calls it "a definitive and unambiguous indicator of a nuclear underground explosion."[45] Some believe that argon-37 could be detected at long range. Professor Roland Purtschert, Department of Climate and Environmental Physics, University of Bern, Switzerland, an expert on argon-37, states,

> I am very confident that instruments could be developed that could operate automatically at remote locations to detect argon-37 from underground nuclear tests. At present, radioxenon detection equipment used by the International Monitoring System concentrates xenon

[41] U.S. Air Force. "Air Force Technical Applications Center," http://www.afisr.af.mil/library/factsheets/factsheet.asp?id=10309.

[42] Argonne National Laboratory, "Krypton," Human Health Fact Sheet, August 2005, 2 p., http://www.ead.anl.gov/pub/doc/krypton.pdf.

[43] The interaction is that when a neutron strikes the nucleus of a calcium-40 atom, the nucleus immediately emits an alpha particle (two neutrons and two protons), producing argon-37.

[44] These neutrons are generated by cosmic rays, naturally-occurring uranium, and other sources.

[45] R. Purtschert, R. Riedmann, and H.H. Loosli, "Evaluation of Argon-37 as a means for identifying clandestine subsurface nuclear tests," Proceedings of the 4th Mini Conference on Noble Gases in the Hydrosphere and in Natural Gas Reservoirs, Potsdam, Germany, February 28-March 2, 2007, p. 1, http://bib.gfz-potsdam.de/pub/minoga/minoga_purtschert-r.pdf.

> isotopes from a large volume of air. It should be possible to separate argon from this same air sample, keep the argon sample as a backup, and measure the fraction of argon-37 when xenon isotopes indicate a possible nuclear explosion. The amount of argon-37 from a nuclear test that is detected would depend on the bomb yield, the rate at which the isotope is released from the underground explosion cavity to the atmosphere, and the sensitivity of the detection system.
>
> I also think that it would be desirable to develop such instruments and deploy them as part of the International Monitoring System. The atmospheric background for argon-37 is very low and constant (about 0.5 to 1 nuclei decaying per second per 1000 cubic meters of air). Civilian sources generate large quantities of xenon and krypton isotopes. As a result, elevated xenon concentrations, for example, become unambiguous indicators of a nuclear explosion only in combination with atmospheric transport modeling. In contrast, there are virtually no civilian sources for argon-37, and the background is low due to argon-37's short half-life. At the same time, the half-life is long enough to allow for the isotope to be transported from the cavity of a nuclear explosion to the atmosphere.[46]

Since argon-37 is produced from neutron reactions on calcium in the soil, neutrons from a nuclear explosion will produce that isotope if calcium is present. It appears that calcium is present almost everywhere. For example, one text states that calcium "is the fifth most abundant element in the earth's crust.... Vast sedimentary deposits of [calcium carbonate], which represent the fossilized remains of earlier marine life, occur over large parts of the earth's surface."[47] It makes up some 4% of the Earth's crust.[48] Even if there were a potential test site devoid of calcium, it would be difficult for a would-be evader to find that site and then to be certain that no calcium was present. In addition, the soil would need to be free of potassium as well because a reaction of a neutron with a potassium atom can produce argon-39, which would be detected in the same way as argon-37.

One value of long-range detection of argon-37 from a nuclear test is that it has a longer half-life than radioxenons, enabling detection at a distance for a longer time. A second value is that ensuring that no argon-37 seeps out, in addition to making sure no other effluents leak out, would increase the difficulty of conducting a nuclear test clandestinely. A third value, pointed out by Charles Carrigan, a geophysicist at Lawrence Livermore National Laboratory, is that detection of a seismic signal characteristic of an explosion followed by simultaneous detection of a spike in radioxenons and in argon-37 would be a compelling indicator of a nuclear explosion.[49]

While the radiation emitted when argon-37 decays has a much lower energy than gamma rays produced by radioactive decay of many other elements, that energy "can be detected with special techniques with relative ease," according to Ted Bowyer, a physicist at Pacific Northwest National Laboratory who specializes in atmospheric detection of radioactive isotopes of noble gases.[50]

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[46] Personal communication, February 5, 2010. These are Professor Purtschert's personal views and not necessarily those of any institution.

[47] N.N. Greenwood and A. Earnshaw, *Chemistry of the Elements*, Oxford, England, Butterworth Heinemann, Publisher, 1998, p. 109.

[48] U.S. National Aeronautics and Space Administration. "World Book at NASA," http://www.nasa.gov/worldbook/earth_worldbook.html.

[49] Personal communication, January 29, 2010.

[50] Personal communication, February 2, 2010.

There are several uncertainties regarding the use of argon-37 for long-range detection of nuclear explosions. First, what is the background level of that isotope from natural and human sources? While the background appears to be low, a definitive conclusion would require further study. Second, can an automated system for detecting this isotope be designed and fielded? While it can be detected in the laboratory, or in the field using manual equipment, an automated system would be needed if detectors are to be placed at remote locations, such as IMS radionuclide stations. Carrigan notes a third uncertainty: the detectability of argon-37 would depend on the rate at which it reaches the surface. If a nuclear test released a large quantity promptly, the isotope would be much easier to detect at long range than if it were released over days or weeks.

Radioactive isotopes of xenon ("radioxenons") are of great value for long-range detection, and the noble gas detection equipment deployed at some IMS radionuclide stations monitors only for them.[51] They are produced by nuclear explosions and nuclear reactors. Nuclear explosions also generate iodine-133 (half-life, 20.8 hours) and iodine-135 (half-life, 6.6 hours), which decay into xenon-133 and xenon-135, respectively. Radioxenons can be detected in minute quantities at great distances, but such detection must be accomplished soon after a nuclear test because of short half-lives. The half-life of xenon-133, an isotope of particular value for identifying nuclear explosions, is 5.24 days, so long-range detection can only be done within about 3 weeks of a test.[52] The other radioxenons of use for monitoring nuclear tests are xenon-135 (half-life, 9.14 hours), xenon-133m (half-life, 2.19 days), and xenon-131m (half-life, 11.84 days).[53]

Several techniques and technologies have greatly improved the ability to detect radioxenons worldwide over the past several decades. As a result, it is possible to detect and identify a particular form of radioxenon thousands of miles from its source within a few weeks of a nuclear test, during which time it will have been reduced to a minute concentration through radioactive decay and mixing with air. IMS equipment takes in large quantities of air, separates and collects any xenon, and compresses the latter to a small volume. Various techniques then acquire data for transmission to the IDC for analysis. One is gamma-ray spectroscopy.[54] Gamma rays are high-energy photons emitted by atomic nuclei when they undergo radioactive decay. Each radioxenon emits gamma rays in a pattern, or spectrum, of energies that uniquely identifies its source. **Figure 1** illustrates the combined spectra of four radioxenons. The horizontal axis has a range of energies measured in keV, or thousands of electron volts; the vertical axis records the number of gamma

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[51] Information provided by Comprehensive Nuclear-Test-Ban Treaty Preparatory Commission, personal communication, July 30, 2009. For a description of how the radioxenon equipment works, see Kalinowski et al., "The Complexity of CTBT Verification. Taking Noble Gas Monitoring as an Example," *Complexity*, vol. 14, no. 1, published online July 14, 2008, pp. 92-93.

[52] Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, "Experts Sure about Nature of the DPRK Event."

[53] Half-life data are from Lawrence Berkeley Laboratory, "Exploring the Table of Isotopes: Isotopes of Xenon (Z=54)," http://ie.lbl.gov/education/parent/Xe_iso.htm. Xenon-131m is of limited value for detecting nuclear explosions because they generate very little of it, and because, given its longer half-life, it is often in the background, at least regionally, generated by nuclear reactors or medical isotope production reactors. Lars-Erik De Geer, "Radioxenon signatures from underground nuclear explosions," poster for the International Scientific Studies Project, Vienna, Austria, June 10-12, 2009, http://www.ctbto.org/fileadmin/user_upload/ISS_2009/Poster/RN-22D%20%28Sweden%29%20-%20Lars-Erik_DeGeer.pdf.

The "m" in xenon-131m and xenon-133m refers to a metastable isomer, which has the same nucleus as xenon-131 or xenon-133, respectively, but in a higher-energy state. In contrast, xenon-133 refers to that isotope in its lower-energy, or ground, state.

[54] For further discussion of gamma-ray spectra, see CRS Report R40154, *Detection of Nuclear Weapons and Materials: Science, Technologies, Observations*, by Jonathan Medalia, Chapter 1 and Appendix.

rays detected at each energy from a sample of a specified mass in a specified time. For example, the spectrum for xenon-133m in **Figure 1** has a peak at 233 keV. Another technique, known as beta-gamma coincidence counting, relies on the simultaneous emission of a beta particle (an electron or positron) and an 81-keV gamma ray when an atom of xenon-133 decays. This signature is unique to xenon-133 and is insensitive to background radiation, so it can be detected even in minute concentrations of xenon-133.[55] Improved sensitivity of radioxenon detection instruments enhances such techniques.

Once radioxenons are detected and identified, the data can be used for long-range detection of nuclear tests in at least three ways. One is to use atmospheric transport modeling (ATM). ATM can help determine the region (as opposed to a precise location) where a nuclear test was conducted by calculating the path of air masses that may be carrying radioactive materials. It uses a computer model to assemble millions of pieces of data collected in near real time by weather satellites, World Meteorological Organization stations,[56] and the IMS network. The model then generates wind speed and direction at many points across a wide area. It can then be "put in motion." Like a movie, the model can be run forward to show the movement of air masses in order to predict the future path of radionuclides released at a precise location. Alternatively, it can be run in reverse to backtrack radionuclides from a specific point (e.g., an IMS radionuclide station) to a region where they may have originated, a process called source region attribution. Source region data may be fused with other data, e.g., IMS seismic observations, using a software graphics tool to narrow the location of a suspected nuclear explosion.

In 2006, IMS noble gas equipment at Yellowknife, Canada, detected xenon-133 some two weeks after the North Korean nuclear test. The measurement could not be traced back to known releases at nuclear facilities (e.g., a nuclear reactor at Chalk River, Canada, used in part to produce radiopharmaceuticals[57]). Instead, ATM showed that the detection was consistent with a hypothesized release of radionuclides taking place in North Korea at the place and time of the event.[58]

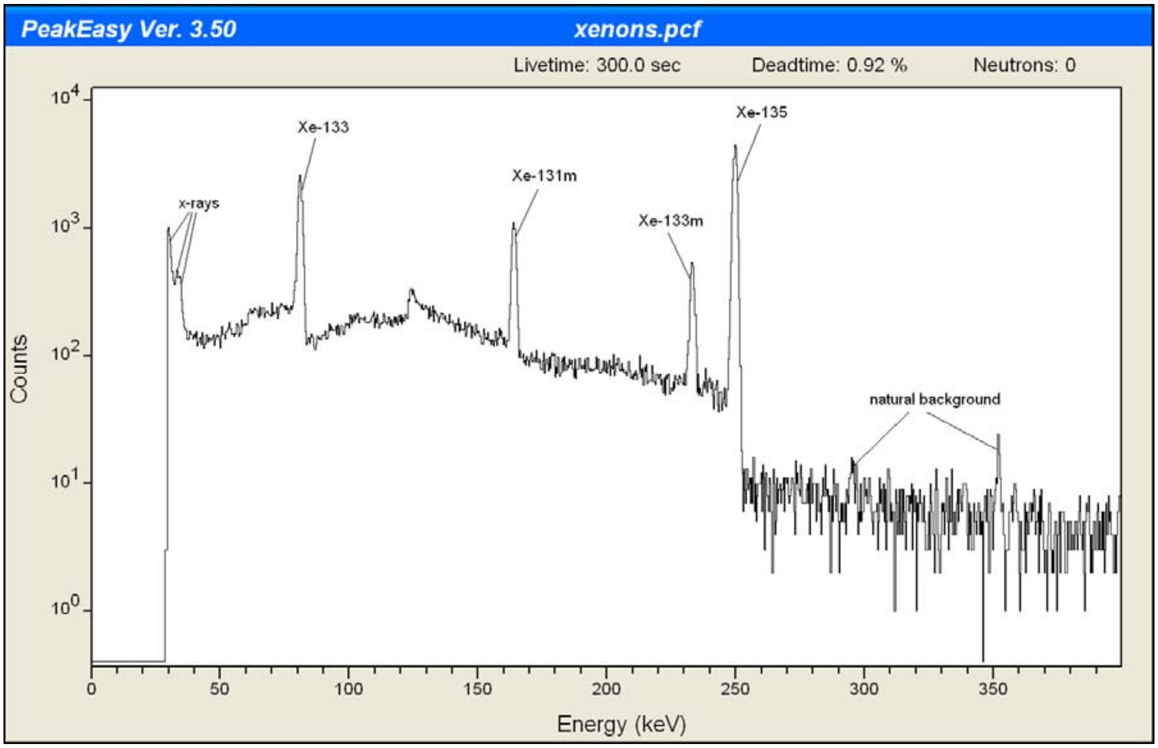
[55] The same approach is used to detect xenon-135, which emits a beta particle and a 250-keV gamma ray simultaneously. Information provided by Joseph Sanders, Sandia National Laboratories, personal communications, September 16 and October 20, 2009.

[56] Comprehensive Nuclear-Test-Ban Treaty Preparatory Commission, "Major Step Forward in Detecting Nuclear Explosions: CTBTO-WMO [World Meteorological Organization] Cooperation Enhances Nuclear Test-Ban Verification," press release, September 1, 2008, http://www.ctbto.org/press-centre/press-releases/2008/major-step-forward-in-detectingnuclear-explosions/.

[57] Atomic Energy of Canada Limited, "Chalk River Laboratories," http://www.aecl.ca/Science/CRL.htm.

[58] P.R.J. Saey et al., "A long distance measurement of radioxenon in Yellowknife, Canada, in late October 2006," *Geophysical Research Letters*, vol. 34 (October 2007), http://www.agu.org/pubs/crossref/2007/2007GL030611.shtml.

Figure 1. Gamma-ray Signatures of Four Radioactive Isotopes or Isomers of Xenon



Source: Provided by Scott Garner, Technical Staff Member, Los Alamos National Laboratory, October 15, 2009.

Notes: Radioactive isotopes of xenon emit gamma rays when they decay. Each of these isotopes emits gamma rays in a particular pattern, or spectrum, with a peak at a particular energy. The gamma rays can be counted, and the number of counts at each energy plotted on a graph. This graph and its peak can be used to differentiate one xenon isotope from another.

Figure 1 shows the lower-energy part of a gamma-ray spectrum taken with a "Detective," a small, commercially-available high-purity germanium detector. The source is a small sample (less than a billionth of a gram each) of xenon-131m, -133, -133m, and -135. According to Garner, "The relative quantities I have displayed here do not even remotely represent the relative quantities seen in actual samples, but were chosen to make it obvious that the different isotopes are easy to tell apart from each other when a strong enough signal is present."

Technical details: The sample is composed of 2.45E-10 grams (7.66E+05 Becquerels) of Xe-131m, 1.50E-11 grams (1.0E+05 Becquerels) of Xe-133, 6.22E-12 grams (1.0E+05 Becquerels) of Xe-133m, and 1.07E-12 grams (1.0E+05 Becquerels) of Xe-135. ("E" is an abbreviation for exponent; one Becquerel is one decay per second.) The source is located 25 centimeters in front of the detector and the data were taken for 300 seconds.

Combining this fact with the level of sensitivity of the detectors,[59] IDC staff concluded that "the containment of any generated xenon (under the hypothesis that this was a nuclear test) was above 99.9 percent" for the 2009 event.[60]

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[59] The detectors can detect one radioactive disintegration per second in 5,000 cubic meters of air. Robert Pearce et al., "The Announced Nuclear Test in the DPRK on 25 May 2009," *CTBTO Spectrum,* September 2009, p. 27, http://www.ctbto.org/fileadmin/user_upload/pdf/Spectrum/09_2009/Spectrum13_dprk2_p26-29.pdf.

[60] Ibid., p. 28. For further information on ATM, see Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, "Atmospheric Transport Modelling and Data Fusion," http://www.ctbto.org/verification-regime/the-international-data-centre/atmospheric-transport-modellingand-data-fusion/page-1-atmospheric-transportmodelling-and-data-fusion/; Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, "Major Step Forward in (continued...)

Second, "most of the environmentally occurring radio-xenon has been produced with nuclear reactors producing radiopharmaceutical materials."[61] Monitoring releases of such reactors can rule out particular reactors as the source of radioxenons at a specific time, as was the case in analyzing the Yellowknife data following the 2006 test. The ratio of certain radioactive xenon isotopes may also prove whether the xenon came from a nuclear test or a nuclear reactor.[62]

Third, if samples are collected and analyzed within hours of a nuclear test, the ratio of xenon-135 to xenon-133 may indicate whether the nuclear explosive was fueled by uranium or plutonium.[63] This information is of interest for analyzing characteristics of the nuclear device, but is not needed to determine whether the test would violate the CTBT if that treaty were to enter into force, which requires only knowing if the test was nuclear. Don Barr, a retired Los Alamos radiochemist with over 50 years of nuclear testing and related experience, calculates that the window for such determination is only an hour or two.[64] Another ratio, xenon-133m/xenon-131m, may enable differentiation between these fuels for a longer time.[65] The IMS could not perform ratio analysis for the 2006 North Korean test because the station at Yellowknife detected only xenon-133 two weeks after the event; xenon-135 was presumably not detected because of its shorter half-life. Jungmin Kang, Frank von Hippel, and Hui Zhang explain a further reason why ratio analysis is of value for only a short time:

> Most of the xenon isotopes released into the atmosphere during the first few hours after a test would have been produced directly from the nuclear fission. In this period, therefore, the ratios of different xenon isotopes could be used to discriminate between plutonium and HEU explosives. Within two days after an explosion, however, most of the xenon isotopes would come indirectly from the decay of radioactive iodines that are produced in almost the same ratio from plutonium-239 and uranium-235 fission.[66]

(...continued)

Detecting Nuclear Explosions," press release, 01 September 2008, http://www.ctbto.org/press-centre/press-releases/2008/major-step-forward-in-detectingnuclear-explosions/; and Tibor Toth, "Building Up the Regime for Verifying the CTBT," *Arms Control Today*, September 2009, p. 10. For several scientific posters on atmospheric transport modeling, see "Atmospheric Transport Modeling/Posters," in the International Scientific Studies website, http://www.ctbto.org/specials/the-international-scientific-studies-project-iss/scientific-contribtutions/atmospheric-transport-modelingposters.

[61] Personal communication, Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, December 8, 2009.

[62] See, for example, De Geer, "Radioxenon signatures from underground nuclear explosions," and Kalinowski et al., "The Complexity of CTBT Verification. Taking Noble Gas Monitoring as an Example," p. 94.

[63] Ibid., and Hui Zhang, "Off-Site Air Sampling Analysis and North Korean Nuclear Test," (deals with the 2006 test), 2007, p. 7, paper presented at the 2007 meeting of the Institute of Nuclear Materials Management, http://belfercenter.ksg.harvard.edu/files/NKSampling_INMM07_Hui.pdf.

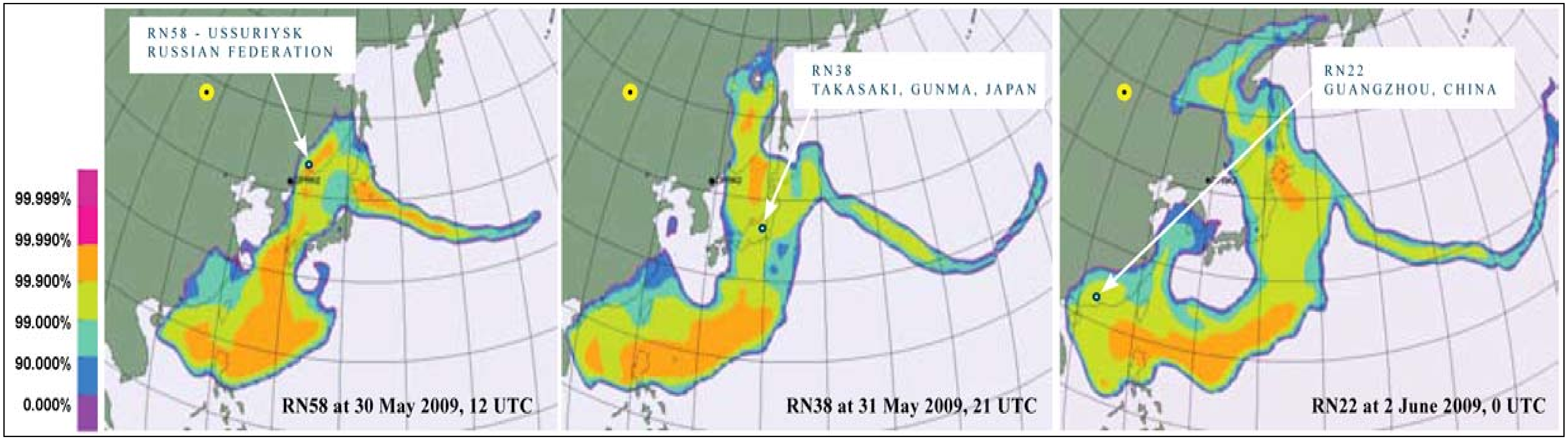
[64] Personal communications, October 20 and 28, 2009.

[65] De Geer, "Radioxenon signatures from underground nuclear explosions."

[66] Jungmin Kang, Frank von Hippel, and Hui Zhang, "The North Korean Test and the Limits of Nuclear Forensics," letter to the editor, *Arms Control Today*, January/February 2007, p. 42.

Figure 2. Atmospheric Transport Modeling

Basis for Concluding 2009 North Korean Test Was >99.9% Contained



Source: Robert Pearce et al., "The Announced Nuclear Test in the DPRK on 25 May 2009," *CTBTO Spectrum,* September 2009, p. 28.

Notes: (modified from text of source report) This figure shows the distribution of a hypothetical radioactive xenon plume at the time of its highest concentration at the IMS radioxenon station indicated in each image. These stations were operational at the time of the 2009 North Korean test. Only those parts of the plume above the minimum detectable concentration are shown. The plume was calculated assuming (1) immediate venting at the time and place of the 2009 North Korean test and (2) zero containment corresponds to the full release of the xenon-133 generated by a four-kiloton nuclear explosion. The key on the left shows the degree of containment of the test. (The online version of this report shows the graphic in color.) For 90% containment, the detectable plume would cover the areas in green, yellow, and orange. For 99.9% containment, the detectable plume would cover only the areas in orange. The fact that these stations did not record xenon-133 signals at the time each would have experienced the maximum concentration of that isotope is the basis on which the authors, who are past or current employees of the International Data Center, "concluded that the containment of any generated xenon (under the hypothesis that this was a nuclear test) was above 99.9 percent." The yellow circle at the upper left of each image is a radioxenon station in Mongolia, the only such station operating in this region at the time of the 2006 North Korean nuclear test.

Thus "while it is true that there is some possibility of determining fuel type from xenon ratios, it would likely be a slim chance."[67]

Nuclear tests may also release particulates, which may contain fission products from the weapon,[68] unfissioned atoms of uranium and plutonium, and melted bits of soil or rock. They range in size from a centimeter in diameter or larger to 0.1 mm or smaller,[69] often less than 0.001 mm. The smaller they are, the farther they can travel before "falling out" to the ground. For decades, particulates have provided not only evidence of a test but other details as well. For example, in 1949, U.S. Air Force "sniffer" aircraft flying over the Pacific Ocean collected particulate samples on filters. A commercial laboratory "dissolved [the filters], chemically separated a selection of fission products such as radioactive isotopes of barium, cerium, molybdenum, zirconium and lead, carefully measured the rates of radioactive decay of the isotopes and counted back to establish when each isotope had been created—its radioactive birthday. Only if all the birthdays were identical could the isotopes have been created in an atomic bomb."[70] Analysis of this sort enabled the United States to conclude that the Soviet Union had conducted its first atomic bomb test on August 29, 1949. According to one report, "During the first 50 years of the nuclear weapons era, radiochemistry techniques were developed and used to determine the characteristics (such as yield, materials used, and design details) of nuclear explosions carried out by the United States and by other countries."[71] As another example of the capability to analyze particulate samples, several researchers, in a 2010 report, analyzed a 7.5-gram sample of debris from "Trinity," the first U.S. nuclear test (1945), and were able to reach several conclusions on the characteristics of the test device.[72] IMS radionuclide stations collect particles on a filter, analyze the gamma-ray spectra on location, and transmit the results to the International Data Center. If a station's filter collects two or more types of particulates that are relevant to CTBT verification, the sample would be shipped to an IMS laboratory to confirm detection and to conduct more detailed investigation. **Figure 3** shows the IMS radionuclide stations closest to North Korea. As it shows, some are not yet in service, some are planned to have radionuclide monitoring stations but not noble gas monitoring equipment prior to entry into force of the CTBT, and there are gaps of many hundreds of kilometers or more between stations.

Background levels of radionuclides in the atmosphere can vary at radionuclide stations due to patterns of weather, season, or climate, and to sources of radioactive material other than current nuclear tests, such as iodine-131 and technetium-99m from hospitals and cesium-137 from past atmospheric nuclear tests. Because of this background variation from place to place and time to

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[67] "Responses to Jonathan Medalia (Congressional Research Service), Questions related to the Comprehensive Nuclear Test Ban Treaty," information provided by DOE and NNSA laboratories, August 2009, p. 2.

[68] Fission products are atoms, usually radioactive, of elements lighter than uranium or plutonium that are produced when uranium or plutonium atoms fission, or split.

[69] U.S. Department of Defense and Department of Energy. *The Effects of Nuclear Weapons,* third edition, compiled and edited by Samuel Glasstone and Philip Dolan, Washington, U.S. Govt. Print. Off., 1977, p. 37.

[70] Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb* (New York, Simon & Schuster, 1995), p. 371. See also Charles Ziegler, "Waiting for Joe-1: Decisions Leading to the Detection of Russia's First Atomic Bomb Test," *Social Studies of Science*, May 1988, pp. 197-229. Radioactive isotopes of lead would be created by neutron bombardment ("activation") of materials in the ground, not by fission of uranium or plutonium in a weapon.

[71] Joint Working Group of the American Physical Society and the American Association for the Advancement of Science, *Nuclear Forensics: Role, State of the Art, and Program Needs,* 2008, p. 3, http://iis-db.stanford.edu/pubs/22126/APS_AAAS_2008.pdf.

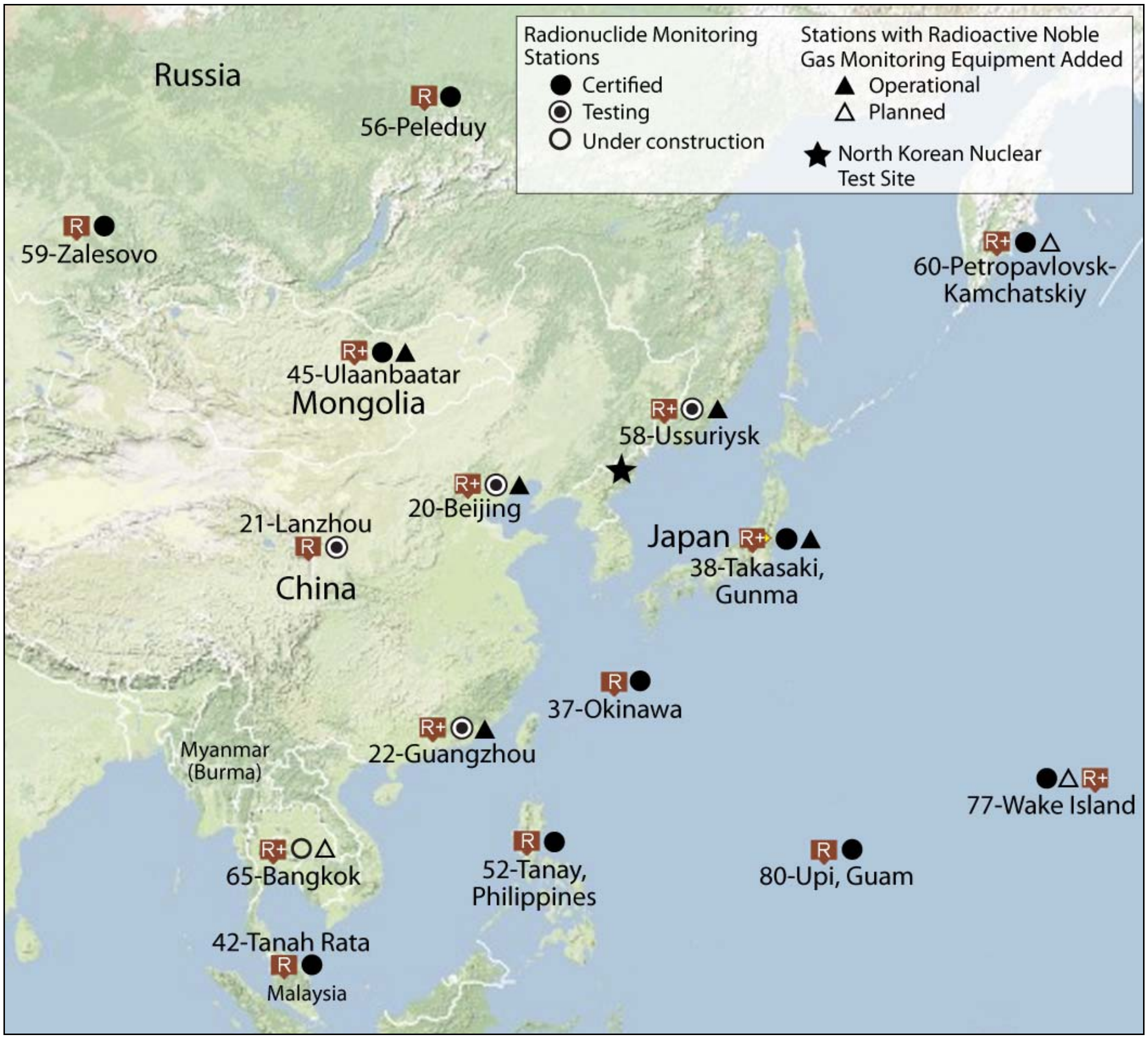
[72] A.J. Fahey et al., "Postdetonation Nuclear Debris for Attribution," *Proceedings of the National Academy of Sciences*, vol. 107, no. 47 (November 23, 2010), pp. 20207-20212; for abstract, http://www.pnas.org/content/107/47/20207.

time, a single measurement may not mean anything unless placed in context with this variation. Accordingly, the Provisional Technical Secretariat, in collaboration with other organizations, measures and characterizes background levels at each radionuclide station to help determine whether an elevated level of radioxenons may have come from a nuclear test.

Releases of radionuclides from an underground nuclear test can occur in any of three ways. One is referred to as "vents." They generally occur promptly, and vary in size from very small (and undetectable at long distances) to large (and easily detectable at long distances). **Figure 4** depicts large vents from two U.S. tests. Vents occur when high-pressure gas generated by an explosion finds a path to the surface, often by a leak in the sealing, or "stemming," of the excavated hole or tunnel, or by a natural fracture in the rock that reaches the ground surface. Unfavorable geology of the test site can contribute to venting in other ways. Certain geologic formations tend to have more preexisting fractures, raising the probability of vent paths. Carbonates in rock produce carbon dioxide when heated by an explosion, raising the pressure of gas in the cavity left by the explosion and thus the probability of venting.

Figure 3. Radionuclide Monitoring Stations of the International Monitoring System

As of February 2010



Source: Map with station locations from Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, station names and symbols by CRS.

Notes: Numbers are those assigned to the stations by Annex 1 to the Protocol of the Comprehensive Nuclear-Test-Ban Treaty. "Certified" stations have been certified by the Provisional Technical Secretariat as meeting its technical standards and are fully operational.

A nuclear explosion turns water in rocks into steam, adding pressure in the explosion cavity that can lead to venting. The Soviet Union found that, at least in some instances, a significant amount of water and carbonate rock led to seeps (discussed next) and venting at its Novaya Zemlya test site, while the opposite conditions at its Semipalantinsk (Kazakhstan) test site did not.[73] Noble gases, being less chemically reactive than other gases and particulates, will always be released by a large vent; seeps and smaller vents release predominantly noble gases, with very little or no

[73] Vitaly Khalturin et al., "A Review of Nuclear Testing by the Soviet Union at Novaya Zemlya, 1955-1990," *Science and Global Security*, vol. 13 (2005), p. 21.

particulate matter.[74] It is likely that the first North Korean test vented, since it apparently released enough radioxenon to be detected two weeks later at Yellowknife.

A second class of release from an underground nuclear test is known as a "seep." Seeps tend to release much smaller amounts of radioactive material, and the released material is generally limited to noble gases and possibly volatile elements, notably radioactive iodine. Seeps do not occur promptly, but instead release at much lower rates, potentially over periods of weeks to months. Seepage can occur through porous rock or small fractures in the rock. Seeps are potentially detectable at the test site by an OSI, offering confirmation of a test. However, seeps occurring more than a few weeks after the detonation are unlikely to release amounts in quantities that could be detected hundreds of miles away by IMS or other monitoring systems.

Seeps and vents both result when high-pressure gases generated by a nuclear explosion escape from the explosion-generated cavity by way of pathways in the surrounding geology or stemming material. When pressure drops sufficiently, seeps and vents cease.

A third class of release, "barometric pumping," relies on a different mechanism that enables gases to reach the surface even after gas pressure in the cavity has dropped to a level of equilibrium with its surroundings. A decrease in atmospheric pressure, such as occurs during a storm, lowers the pressure in fractures terminating near the surface so that the relative pressure in the cavity end of a fracture becomes greater. This pressure differential draws noble gases upward toward the Earth's surface. As gases flow upward in a fracture, they also diffuse into the porous walls of the fracture and are temporarily stored there even when increased atmospheric pressure causes gases in a fracture to flow downward. The stored gases are available to diffuse from the porous walls into the next upward flow of gases in the fracture. Thus barometric pumping creates a ratcheting effect that eventually can transport noble gases to the surface after seeps and vents induced by pressure within the cavity have ceased.[75] Barometric pumping would probably not aid long-range detection because quantities of radioactive noble gases released through this mechanism are small and can take many weeks to reach the surface, during which time most of these gases will have undergone radioactive decay, but it can produce enough of these gases to be detected by an OSI.

How Can Radioactive Material Be Contained?

Containment is no simple matter. According to a National Academy of Sciences report, "Recent Russian papers documenting Soviet nuclear testing state that all underground tests at Novaya Zemlya and about half the underground tests at the Semipalatinsk test site in Kazakhstan resulted in release of radioactivity."[76] While fewer U.S. nuclear tests released radioactivity, containment failures did occur. For example, **Figure 4** shows the "Des Moines" nuclear test. It was conducted in June 1962 at the Nevada Test Site, and had an explosive yield of 2.9 kilotons, comparable to

[74] Information provided by Joseph Sanders, Sandia National Laboratories, personal communication, September 11, 2009.

[75] See C.R. Carrigan et al., "Trace Gas Emissions on Geological Faults as Indicators of Underground Nuclear Testing," *Nature,* vol. 382, August 8, 1996, pp. 528-531; and Lars-Erik De Geer, "Sniffing out Clandestine Tests," *Nature,* vol. 382, August 8, 1996, pp. 491-492.

[76] John Holdren (chair) et al., *Technical Issues Related to Ratification of the Comprehensive Test Ban Treaty,* Committee on Technical Issues Related to Ratification of the Comprehensive Test Ban Treaty, National Academy of Sciences, National Academy Press, Washington, 2002, p. 45. The source cited is V.N. Mikhailov et al., *Northern Test Site: Chronology and Phenomenology of Nuclear Tests at the Novaya Zemlya Test Site,* July 1992.

the "few kilotons" of yield that the U.S. Office of the Director of National Intelligence assessed for the North Korean event of May 2009. **Figure 4** also shows "Baneberry," a 10-kiloton test conducted at the Nevada Test Site in December 1970.

Figure 4. Venting of Nuclear Tests

"Des Moines" 1962 (left), "Baneberry" 1970 (right)

Source: "Des Moines," Lawrence Livermore National Laboratory; "Baneberry," U.S. Department of Energy

The United States went to great lengths to contain nuclear tests. Containment relies on a detailed understanding of how well the geology around the nuclear device may contain the explosion and an ability to engineer containment, such as by sealing the test shaft. Barr said, "Deep burial of a nuclear device, combined with gas blocking techniques, virtually eliminates the seepage of noble gases to the surface, though some such gases might occasionally be detected, but only at the surface above the detonation point."[77] On the other hand, knowledge of the geology surrounding a nuclear explosive is imperfect, so there may be hidden pathways for vents and seeps. As a result, there is an element of art and chance to containment:

> The earth, from the surface to the mile or so in depth that has been used in underground nuclear testing is an inhomogeneous body of materials ... it is not possible to know all, or even most, of the details of the medium where the detonation takes place.
>
> So, empirical rules are developed, approximations are made and are used in computer codes to model the behavior of the earth materials following a detonation, but there is a further complication. Important processes occur during a time span that ranges from fractions of a microsecond to hours....

[77] Personal communication, November 21, 2007.

> In such a situation experience and empirical evidence from previous detonations assumes a considerable importance when trying to judge what will happen when a particular detonation takes place in some specific location. The experience and evidence that there is has been gathered over the years, sometimes in a costly fashion.[78]

The unclassified U.S. literature contains information on containing a test. A 1977 publication by the Departments of Defense and Energy provides data on how deeply to bury a nuclear explosive device to contain radioactive gases.[79] A 1989 Office of Technology Assessment (OTA) report provides technical details. It notes that containment properties of rock depend on its type, structure, and water content; lists some U.S. procedures used to evaluate containment; and provides diagrams of mechanisms used to contain various types of nuclear tests.[80] A 1995 report sponsored by Lawrence Livermore National Laboratory and the Defense Nuclear Agency provides further details.[81]

Better techniques can greatly improve containment. For the United States, improvement occurred in two major steps. The Limited Test Ban Treaty, which bans nuclear tests in the atmosphere, in space, and under water, was signed on August 5, 1963. Before that date, "no specific test containment design criteria existed. Therefore, while radioactive effluents released from underground tests conducted during this period [September 15, 1961, to August 5, 1963] were not always expected, any effluent releases that did occur were not considered accidental, or even unexpected."[82] After August 5, 1963, "all tests (except four Plowshare cratering tests) were designed to be completely contained underground."[83] Following Baneberry, the Atomic Energy Commission instituted new containment practices.[84] In consequence, while the Department of Energy reported that 101 of 335 U.S. nuclear tests conducted from August 5, 1963, through 1970 accidentally released radiation, it reported that 6 of 388 tests conducted from 1971 through the most recent U.S. nuclear test, in 1992, did so.[85] In addition, small amounts of noble gases seeped into the atmosphere and were detected, onsite only, days to years after five tests from 1984 to 1989,[86] and radioactive material was released intentionally after quite a few post-1970 tests, such as by drilling back into the cavity to collect samples for analysis.[87] The 1989 OTA report provided

[78] Lawrence Livermore National Laboratory and U.S. Department of Defense. Defense Nuclear Agency, *Caging the Dragon: The Containment of Underground Nuclear Explosions*, DOE/NV-388 and DNA TR 95-74, 1995, by James Carrothers, p. 1, http://www.scribd.com/doc/6602337/Caging-the-Dragon-The-Containment-of-Underground-Nuclear-Explosions. (On the cover: "Distribution of this document is unlimited.")

[79] U.S. Department of Defense and Department of Energy. *The Effects of Nuclear Weapons,* third edition, p. 261.

[80] U.S. Congress. Office of Technology Assessment. *The Containment of Underground Nuclear Explosions.* OTA-ISC-414, October 1989, pp. 31-55, available at http://www.nv.doe.gov/library/publications/historical/OTA-ISC-414.pdf.

[81] Carrothers, *Caging the Dragon,* 726 p.

[82] U.S. Department of Energy. Nevada Operations Office. *Radiological Effluents Released from U.S. Continental Tests, 1961 through 1992,* DOE/NV-317 Rev. 1, UC-702, August 1996, p. 2, http://www.nv.doe.gov/library/publications/historical/DOENV_317.pdf.

[83] Ibid. "Plowshare" tests explored peaceful uses of nuclear explosions, such as digging canals or harbors, in the 1960s and 1970s. Tests intended to create large craters for such purposes of course could not be contained.

[84] Office of Technology Assessment. *The Containment of Underground Nuclear Explosions,* p. 32. The Atomic Energy Commission was a predecessor agency of the Department of Energy.

[85] U.S. Department of Energy. Nevada Operations Office, *United States Nuclear Tests, July 1945 through September 1992,* DOE/NV—209-REV 15, December 2000, pp. 30-89, http://www.nv.doe.gov/library/publications/historical/DOENV_209_REV15.pdf.

[86] U.S. Department of Energy, *Radiological Effluents Released from U.S. Continental Tests, 1961 through 1992,* pp. 210, 211, 222, 223, 231.

[87] U.S. Department of Energy, *Radiological Effluents Released from U.S. Continental Tests, 1961 Through 1992.*

another view of the effectiveness of post-Baneberry containment: "If the same person had been standing at the boundary of the Nevada Test Site in the area of maximum concentration of radioactivity for every test since Baneberry (1970), the person's total exposure would be equivalent to 32 extra minutes of normal background exposure (or the equivalent of 1/1000 of a single chest x-ray)."[88] Some U.S. nuclear tests that were not reported as releasing radioactive material might have done so, but the amount released may have been below the detection threshold for instruments available at the time.

While there is no publicly-available information on whether North Korea attempted to contain its second test, and if so what methods it used, containment could have resulted from one of the following factors, or a combination of several:

Lessons learned from the first test: As noted, a nuclear test provides data for many disciplines involved with the test. North Koreans involved in containment would have learned lessons from the first test applicable to the second test, including how such factors as stemming methods, depth of burial, and type of rock affect containment.

Lessons learned from the experience of other nations: These lessons deal with such factors as depth of burial, type of stemming, and geologic considerations, as discussed previously.

Use of a higher-yield nuclear device: It can be harder to contain lower-yield underground nuclear explosions than higher-yield ones. The latter produce more energy, which pushes outward against the surrounding rock, which then rebounds toward its original position. OTA states, "the rebounded rock locks around the cavity forming a stress field that is stronger than the pressure inside the cavity. The stress 'containment cage' closes any fractures that may have begun and prevents new fractures from forming."[89] A nuclear explosion melts rock, forming a glass-like substance. These effects can seal leak paths, especially fractures in the rock through which noble gases or particulates might escape. Sealing is more likely for a higher-yield test. While both North Korean tests were of low yield, the second reportedly had several times the yield of the first.

Good luck: North Korea may have, by chance, selected a test site with solid rock having no fissures, or with another geology favorable to containment, and may have used enough material to seal the test shaft or tunnel solidly enough to contain radioactive material. As noted, even in the period before 1963, when there was no particular effort made to contain U.S. underground nuclear tests, quite a few of them did not have measured releases of radioactivity.

Venting below the detection threshold: The standard for IMS radioxenon equipment is the ability to detect one atom of xenon-133 decaying per second per thousand cubic meters of air (the minimum detectable concentration).[90] In practice, the equipment is more sensitive than that.[91] While this threshold has become lower over the years, it is greater than zero. It is thus possible that the test vented, but that the quantity of material released was below the detection threshold.

[88] Office of Technology Assessment, *The Containment of Underground Nuclear Explosions,* pp. 4-5; original text bold.

[89] Ibid., p. 34.

[90] Mika Nikkinen, Matthias Zahringer, and Robert Werzi, "The Radionuclide Processing System of the CTBTO," poster presented at International Scientific Studies 2009, http://www.ctbto.org/fileadmin/user_upload/ISS_2009/Poster/RN-30%20%28PTS%29%20-%20Mika_Nikkinen%20etal.pdf.

[91] "Responses to Jonathan Medalia," August 2009, p. 1.

Nonnuclear explosion: The May 25 event may not have been a nuclear test, which would explain the lack of radioactive effluents.

While evidently not the case for the 2009 test, as **Figure 2** implies, attention to atmospheric conditions could impede detection of radionuclides and thus contribute to the appearance of containment. Waiting to conduct a test until wind currents were blowing away from IMS or national radionuclide stations could prevent these stations from collecting radionuclides.

Given the learning curve, potential failure modes of containment, and the sensitivity of detection equipment, it would be a significant achievement if North Korea had, by design, been able to hold venting of its second test to below the current detection threshold. At the same time, one test that apparently did not release radioactive effluents is too small a sample size from which North Korea, the United States, or other nations could draw firm conclusions as to North Korea's containment capability. That nation's ability to contain any future tests thus bears close watching.

Potential Value of Containment for North Korea

The ability to contain radioactive material from the 2009 test offers several potential benefits for North Korea. First, careful attention to containment should reduce the likelihood of a major venting of fallout similar to Baneberry. Venting would arguably not be in North Korea's interests. Fallout reaching China could harm North Korea's relationship with its major ally, perhaps leading China to increase pressure on North Korea to halt nuclear testing or even its nuclear weapons program. Fallout reaching Russia could have a similar effect. Fallout on Japan or South Korea would likely antagonize them. Fallout on North Korea could contaminate land. Avoiding fallout is reason enough for North Korea to try to improve its containment capabilities.

Second, if particulates containing uranium or plutonium vented and could be collected at a distance, other nations could analyze them in an attempt to gain data on weapon characteristics, helping to track problems and progress of North Korea's nuclear weapons program. This is another reason for North Korea to focus on containment of its underground explosions.

Third, absence of radionuclides from a nuclear test, as a result of containment, could make it harder to muster the 30 votes in the 51-member CTBTO Executive Council needed to authorize an OSI by providing scientific cover to nations that wanted to deny a request for an OSI on political grounds. This approach could be more significant for a nation with more allies than North Korea has. On the other hand, a lack of radioactive noble gases combined with a nuclear explosion-like seismic signal and other technical evidence would provide a compelling technical case for requesting an OSI. Of course, the surer way for North Korea to avert OSIs would be for that nation not to ratify the CTBT, keeping it from entering into force.

Fourth, and more speculatively, successful containment could enable other nations to conduct nuclear tests in North Korea. This does not appear to have happened, but Iran is a possible candidate. The two have a record of conventional arms trade and missile cooperation.[92] Events in 2009, such as the discovery of a covert facility for uranium enrichment, increased suspicions that

[92] See, for example, Jim Wolf, "North Korea, Iran Joined on Missile Work: U.S. General," *Reuters*, June 11, 2009, http://www.reuters.com/article/newsOne/idUSTRE55A4E720090611. See also CRS Report RL30613, *North Korea: Back on the Terrorism List?* by Mark E. Manyin.

Iran is pursuing nuclear weapons. It is not unprecedented for one nation to "host" another's nuclear tests: the United Kingdom conducted 24 tests jointly with the United States at the Nevada Test Site between 1962 and 1991.[93]

Iranian testing in North Korea would aid the latter by providing data for weapons development and giving the impression that its nuclear weapons program was proceeding rapidly. Such testing would aid Iran by helping it develop nuclear weapons while potentially avoiding consequences of a test in Iran, such as an attack on its nuclear facilities. In particular, an extremely low yield test (e.g., 0.5 kilotons) conducted in Iran might be interpreted as a failure, inviting attack before the weapons program developed further, while a larger test (e.g., 20 kilotons) in Iran might deter attack. Conducting one or two tests in North Korea might avert the former contingency. This arrangement would demand high confidence in North Korea's containment ability so as to deny radioactive samples by which the test could be attributed to its partner. Analysis of these samples might reveal if the bomb fuel was uranium or plutonium, details of the bomb design, and perhaps which reactor produced the fuel. While particulate samples convey more data than do gases, the ability to contain gases would imply a strong ability to contain particulates.

Several factors argue against this scenario. Iran might use nuclear tests in Iran to demonstrate its nuclear capability as a deterrent, to gain leverage in the Middle East, and to show its people that other nations could not dictate its nuclear policies. Iran might believe it could deter a U.S. strike on its nuclear facilities by its nuclear threat or the prospect of retaliation against U.S. forces in the area. Iran might discount the threat of an Israeli strike if it felt that Israel could only inflict a temporary setback to its nuclear program. North Korea might halt nuclear tests if it thought it could make major gains in the Six-Party Talks. North Korea and Iran might not have high confidence in North Korea's ability to contain nuclear tests. There are questions about the reliability of media reports on Iranian-North Korean cooperation in the nuclear area.

Developments of late 2010 may soon render this scenario overtaken by events. According to a report of November 2010, North Korea is pursuing uranium enrichment but not plutonium reprocessing. As a result, it would be difficult to use uranium debris collected from a nuclear test to determine whether the test device was manufactured by North Korea, Iran, or another nation. Details are as follows.

Siegfried Hecker, Co-Director, Center for International Security and Cooperation, Stanford University, and Director Emeritus of Los Alamos National Laboratory, reported on a visit to North Korea's nuclear complex at Yongbyon. North Korean officials showed him and other U.S. visitors "a new facility that contained a modern, small industrial-scale uranium enrichment facility with 2,000 centrifuges that was recently completed." Further, "we were told that they began construction in April 2009 and completed the operations a few days ago." Hecker reported that the chief process engineer told him that the centrifuges were not of a first-generation P-1 design, and inferred that they were most likely of the more advanced P-2 design. He wrote, "I expressed surprise that they were apparently able to get cascades of 2,000 centrifuges working so quickly, and asked again if the facility is actually operating now—we were given an emphatic, yes." He stated that "the greatest concern is that a facility of equal or greater capacity, configured to produce HEU, exists somewhere else. Such a facility would be difficult to detect as demonstrated by the fact that this facility was undetected in the middle of the Yongbyon fuel

[93] U.S. Department of Energy, *United States Nuclear Tests, July 1945 through September 1992,* pp. xvi, 18-89.

fabrication site."[94] Another analysis also raised the possibility that the enrichment facility at Yongbyon "may not be the first gas centrifuge plant that North Korea has built. It is possible that North Korea built another plant previously and either transferred it to Yongbyon or simply built another one based on its experience of bringing the first, perhaps smaller, one into operation."[95]

North Koreans told Hecker that the centrifuges were being used to produce low-enriched uranium (LEU) as fuel for a nuclear power plant. (LEU cannot be used for a nuclear weapon.) However, Hecker stated that the centrifuges could be rearranged to produce up to 40 kg of highly-enriched uranium (HEU) per year; HEU can be used in a nuclear weapon. Regarding plutonium, he saw no activity at the facility for reprocessing plutonium; that and other data led him to conclude that "Pyongyang has apparently decided not to make more plutonium or plutonium bombs for now. My assessment is that they could resume all plutonium operations within approximately six months and make one bomb's worth of plutonium per year for some time to come."[96]

It might in theory be possible to determine the provenance of a weapon from analysis of particulate debris, but this could be difficult in practice. For example, detecting uranium in debris from a nuclear test conducted inside North Korea would not be proof that the weapon was North Korean, even if it could be determined that the uranium was of North Korean manufacture: "David Asher, who helped direct efforts to counter North Korea's proliferation activities in the George W. Bush administration … [said] 'My fear is that just as Iran's demands for enriched uranium for a bomb are expanding, North Korea may be in the position to begin supplying.'"[97]

Another North Korean Test?

Prospects for Another Test: Reports Are Mixed

Many press reports of late 2010 speculated on whether DPRK was preparing another nuclear test and when such a test might occur:

- "Unification Minister Hyun In-taek on [October 22] said the government is watching North Korea closely for signs that the Stalinist country is preparing another test…. But Hyun added the chances are 'low' at the moment."[98]
- "A U.S. reconnaissance satellite has detected signs of North Korea preparing for a nuclear test in North Hamgyong Province, where it had conducted two earlier tests in October 2006 and May 2009. A South Korean government source on [October 20] said 'brisk movement' of vehicles and people has been detected in

[94] Siegfried Hecker, "A Return Trip to North Korea's Yongbyon Nuclear Complex," November 20, 2010, http://iis-db.stanford.edu/pubs/23035/Yongbyonreport.pdf.

[95] David Albright and Paul Brannan, "Satellite Image Shows Building Containing Centrifuges in North Korea," Institute for Science and International Security, November 21, 2010, http://isis-online.org/isis-reports/detail/satellite-image-shows-building-containing-centrifuges-in-north-korea/. See also David Albright and Paul Brannan, "Taking Stock: North Korea's Uranium Enrichment Program," Institute for Science and International Security, October 8, 2010, http://www.isis-online.org/uploads/isis-reports/documents/ISIS_DPRK_UEP.pdf.

[96] Hecker, "A Return Trip to North Korea's Yongbyon Nuclear Complex."

[97] Jay Solomon and Adam Entous, "North Korea Nuclear Fears Grow," *Wall Street Journal,* November 22, 2010, p. 8.

[98] "Chances of Another N.Korean Test 'Low,'" *Chosun Ilbo* (Republic of Korea), October 25, 2010.

Punggye-re recently…. However, it seems unlikely that the North will conduct a third nuclear test in the immediate future since current activities there suggest it will take 'about three months' to prepare, the source added."[99]

- The Defense Minister of the Republic of Korea, Kim Tae-Young, "told lawmakers the North is 'constantly seeking to make its nuclear weapons smaller' for possible future delivery by ballistic missiles or bombers…. But Kim said he sees 'no clear signs' so far that the communist country is preparing for another test."[100] (Nuclear testing is one way to reduce the size of nuclear weapons.)
- "A government official says Seoul has yet to find substantial evidence that suggests that North Korea is seeking to conduct another nuclear test."[101]
- "New satellite imagery shows renewed activities in northeastern North Korea where Pyongyang conducted its second nuclear test in May 2009, but it is too early to say whether another test is imminent, a U.S. analyst told Kyodo News on Wednesday. Images captured by DigitalGlobe Inc., an American company specializing in geographical imagery, suggest work is being carried out at the site in North Hamgyong Province, according to Allison Puccioni, an image analyst for the defense intelligence group Jane's. She said one of the images taken on Oct. 16 shows at least six vehicles or pieces of equipment at the site's operation base. There also appears to be a 12-meter-wide pile of excavated debris in the base's staging area, indicating that tunneling is under way."[102]
- "A Japanese government official said … 'the timing cannot be specified, but a nuclear test could happen any time.'"[103]
- "A Cheong Wa Dae official said, 'North Korea is up to something, but we don't expect anything to happen right now.' Judging from the depth of the shaft that has been dug so far, it will apparently take three to six more months before a nuclear test can be conducted."[104]
- "A South Korean government official says that it has yet to confirm detailed proof that North Korea is preparing for another nuclear test at a nuclear testing site in Gilju County, North Hamgyeong Province."[105]

From the foregoing and similar reports, it appears that as of late November 2010, North Korea is conducting work at its nuclear test site, that this work is consistent with preparations for a nuclear test, and that the site is not ready for a nuclear test. It is not clear if the work is farther along than the reports imply; or if the apparent excavation is a ruse, with no actual work done; or if preparations for a nuclear test are underway at another site elsewhere in North Korea.

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[99] "Is N.Korea Preparing for Another Nuke Test?," *Chosun Ilbo* (Republic of Korea), October 21, 2010.

[100] "N.Korea Seeks to Develop Smaller Nuclear Warheads: Minister," *Agence France-Presse,* November 2, 2010.

[101] "Gov't Yet to Confirm Whether NK Is Preparing Another Nuke Test," *KBS World News,* November 17, 2010.

[102] "Satellite Images Confirm New Activities at N.Korea Nuke Test Site," *Kyodo News* (Japan), November 17, 2010.

[103] "More Reports Confirm Activities at N.K. Nuke Site," *Korea Herald,* November 19, 2010.

[104] "N.Korea's Twin Nuclear Threats," *Chosun Ilbo* (Republic of Korea), November 20, 2010. Cheong Wa Dae, the Blue House, is the executive office and official residence of the President of South Korea.

[105] "S.Korea Has Yet to Confirm NK's Possible Nuke Test," *KBS World News,* November 20, 2010.

What to Look for in the Event of Another Test

The material presented earlier in this report indicates many data points that Congress may wish to look for in government and media reports on a future North Korean test. The data can be used to improve an understanding of the test and its significance:

- Could the event have been nonnuclear? Was the evidence seismic only? Was there evidence of a large quantity of conventional explosives being brought to the test site?
- Was the test nuclear? What was the evidence of the test, and how reliable is it? Were radionuclides detected in addition to seismic signals? If radionuclides were detected, were they only in the form of gases, or were particulates detected as well? If gases were collected, were they collected soon enough to analyze the ratio between xenon isotopes?
- What was the estimated yield of the test? What is the range of credible estimates?
- Is there any evidence of advanced design, such as increased yield, boosting, or steps toward a thermonuclear weapon (hydrogen bomb)? For example, a mixture of deuterium and tritium gases (isotopes of hydrogen) is used to boost the yield of modern nuclear weapons. Tritium must be manufactured. Is there any evidence (whether from the test or other intelligence sources) of production or use of tritium?
- How well did the IMS and other sensors detect the event? How quickly were seismic signals detected, analyzed, and distributed? How many IMS seismic stations detected the event? What other stations (hydroacoustic, infrasound, radionuclide) detected it? Did the projected path of the air mass over the test site at the time of the test and for several days thereafter coincide with the actual path?
- Was there any reporting on how well U.S. national technical means of verification, such as aircraft to detect debris, satellites, and seismic stations not part of IMS, performed?
- Conversely, how effectively did North Korea contain the test? Was there evidence of containment techniques or, if the test was well contained, did containment appear to be mainly a function of deep burial?
- Was there any indication of foreign assistance to, or observation of, the test? Was there any indication that the test was conducted for a nation other than North Korea?

Issues for Congress

The 2009 North Korean test raises at least two issues for Congress. What does the test imply for U.S. ability to verify compliance with the CTBT? And what unilateral and multilateral steps might Congress mandate or encourage to improve monitoring and verification capability?

Implications for the CTBT

Supporters and opponents of the CTBT will likely draw opposing conclusions on what the absence of detectable radionuclides from the 2009 test indicates. Here are points they might raise in a future debate.

Opponents might argue that without detection of radionuclides there is no proof that North Korea conducted a nuclear test. For example, the May 2009 event might have been a large conventional explosion conducted to inflate the appearance of progress in North Korea's weapons program.

The treaty's supporters might respond that the ability of the IMS seismic component to pick out signals characteristic of an explosion originating in the area of the suspected test from the many seismic signals occurring each day shows the capability of the IMS. As another example, the IMS detected the 2009 event seismically, and identified it as an explosion, before North Korea announced it.[106] More generally, the 2009 test shows that an attempt to evade detection would also have to contain radionuclides and suppress other signatures, a more difficult task than suppressing only one signature. Suspicious seismic signals and an absence of radionuclides, it is argued, would surely lead to calls for an OSI.

Opponents might counter that OSIs could not happen unless the treaty entered into force, and that North Korea is unlikely to ratify the treaty, thereby preventing entry into force, as long as it has any interest in future nuclear tests. Even if North Korea ratified the treaty, it could bar inspections of its territory, and if it allowed them, inspectors might not find proof that a test occurred. While the case could be referred to the United Nations, CTBT opponents would see only a slim likelihood of that body taking effective action.[107]

Supporters recognize that OSIs could not be conducted under the treaty without entry into force, and see that as a benefit of entry into force. They believe that OSIs have a good chance of finding a "smoking gun," and that the U.N. would adopt stringent sanctions on North Korea in response to nuclear tests conducted after the treaty had entered into force. They see a refusal by a state party to permit inspections as *prima facie* evidence of a violation.

One generally-accepted means of evading detection of nuclear tests, especially low-yield tests, is "decoupling," testing in a large underground cavity to muffle the seismic signal. Opponents could argue that a decoupled test conducted in a manner that prevented release of radionuclides, such as deep under a mountain, might go undetected by radionuclide sensors as well as seismographs, and that the other two IMS technologies, infrasound and hydroacoustic, would not be expected to detect a test of this sort, so all IMS technologies might be circumvented simultaneously. Opponents might argue further that the ability of the IMS to detect the 2006 and 2009 tests does not show that that system can detect clandestine tests because neither test was conducted evasively. (North Korea announced both of them.) In this view, any cheater would use evasive methods, so the IMS has merit only insofar as it can detect evasive tests.[108]

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[106] Personal communication, Annika Thunborg, Comprehensive Nuclear-Test-Ban Treaty Organization Preparatory Commission, December 8, 2009.

[107] See Senator Jon Kyl, "Why We Need to Test Nuclear Weapons," *Wall Street Journal,* October 21, 2009, p. 23.

[108] For discussions of decoupling and other evasion scenarios, see David Hafemeister, "CTBT Evasion Scenarios: Possible or Probable?," *CTBTO Spectrum,* issue 13, September 2009, pp. 22-25, http://www.ctbto.org/fileadmin/user_upload/pdf/Spectrum/09_2009/Spectrum13_hafemeister_p22-25.pdf, and Robert Barker, "CTBT Monitoring (continued...)

Supporters question the feasibility of decoupling, or otherwise hiding, a test of more than 1 or 2 kilotons. They note that the IMS has detected seismic signals down to a small fraction of a kiloton; that it is difficult to hide the rock that must be removed to create an underground cavity; and that, despite precautions, an evader cannot count on near-perfect containment. The merits of various evasion techniques have been debated for decades.[109]

Entry into force requires ratification by North Korea, among others, yet that nation's ratification may be difficult to obtain. To circumvent the problem, some CTBT supporters have suggested bringing the treaty into force provisionally.[110] This apparently would mean that states that had ratified the treaty would behave among themselves as if the treaty had entered into force, permitting OSIs among these states and formal operation of the structures of the CTBTO. But there are problems with provisional entry into force. First, a state not party to provisional entry into force might conduct a large conventional explosion designed to simulate a nuclear explosion so as to give the impression of progress on its nuclear program. Since the IMS is designed to detect nuclear tests only, it would not detect signatures that would identify a test as nonnuclear. Second, since a state could conduct a test in a host state that was not party to provisional entry into force, it would be important to attribute the test to learn if a state party to provisional entry into force had conducted the test; that would be difficult to do if the test were well contained. "Regular" entry into force would address both concerns. OSIs could reveal if the test was nuclear or conventional, and attribution would not matter for the treaty's verification regime because any nuclear test would violate the CTBT.

Improving Monitoring and Verification Capability

Key problems for analyses of the 2009 North Korean event were determining whether it was a nuclear explosion and learning more about it. In examining budgets and programs, Congress may wish to consider various means of improving U.S. and international ability to monitor nuclear testing by North Korea and other nations. The preceding sections of this report lead to several possible means to do this. They fall into several categories: (1) conduct research to better characterize nuclear explosions and containment, (2) deploy more monitoring equipment, (3)

(...continued)

Limitations & Verification Implications: Cheating Scenarios," presentation to the National Academies' CTBT Review Committee, September 9, 2009. The latter document is available through the committee's website, http://www8.nationalacademies.org/cp/projectview.aspx?key=49131; follow the link to the Public Access Records Office at the bottom of the page, and use that link to file a request.

109 John Holdren (chair) et al., *Technical Issues Related to Ratification of the Comprehensive Test Ban Treaty*, Committee on Technical Issues Related to Ratification of the Comprehensive Test Ban Treaty, National Academy of Sciences, National Academy Press, Washington, 2002, pp. 46-48. See also Harold Karan Jacobson and Eric Stein, *Diplomats, Scientists, and Politicians: The United States and the Nuclear Test Ban Negotiations,* University of Michigan Press, Ann Arbor, 1966, pp. 153-154.

110 United Nations. General Assembly. "Letter dated 29 June 2006 from the Permanent Representative of Sweden to the United Nations addressed to the Secretary-General," Annex, "Weapons of Terror: Freeing the World of Nuclear, Biological, and Chemical Arms," document A/60/934, July 10, 2006, p. 13, http://www.wmdcommission.org/files/english.pdf; and Martin Matishak, "Nuclear Test Ban Could Become Reality Without North Korea, Experts Say," *Global Security Newswire,* June 4, 2009, http://www.globalsecuritynewswire.org/gsn/nw_20090602_5876.php. Jessica Tuchman Mathews said, "If only North Korea and Iran remain [as states that must ratify the CTBT for it to enter into force], the more than 160 nations that have joined the treaty will not allow them to block it. An amendment will be drawn that allows provisional entry into force without them." Jessica Tuchman Mathews, "This Time, Ban the Test," *International Herald Tribune,* October 21, 2009, http://carnegieendowment.org/publications/index.cfm?fa=view&id=24021.

improve the performance of monitoring systems, and (4) look for new signatures to help determine if a test is nuclear. Note that government agencies that conduct programs to improve monitoring and verification capability develop strategic plans for their work and update them annually; the options presented here would need to be prioritized against existing programs.[111]

Conduct Research to Better Characterize Nuclear Explosions and Containment

Conduct Basic Research on Containment

Radioactive gases, and especially radioactive noble gases, are an important sign of a nuclear explosion. Yet Raymond Jeanloz, Professor of Earth and Planetary Science, University of California at Berkeley, said: "The science underlying the containment of gases in the Earth's crust is poorly understood. The U.S. nuclear test program focused on containment of particulates. The program did not try to gain a full understanding of what determines how or when gases are contained, but instead developed practical solutions to containment."[112] A better understanding of the science of how the Earth contains gases, especially in the case of nuclear tests, should help evaluate North Korean containment efforts.

Evaluate the Adequacy of Monitoring of North Korean Containment

Given the potential significance of North Korean efforts to contain radioactive material from nuclear tests, it may be of value to have the Intelligence Community analyze the first two North Korean nuclear tests to see what containment methods were used, and in what ways, if any, North Korea modified those methods for its second test. Similarly, it may be of value for that community to pay particular attention to containment methods in monitoring North Korean preparations for any future nuclear test. The Intelligence Community could report its findings on a classified basis to the congressional committees of jurisdiction.

Conduct Research to Improve Atmospheric Transport Modeling

Improving atmospheric transport modeling could improve the accuracy with which it could track radionuclides back to their location of origin, or predict the path of an air mass carrying radioactive materials.

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[111] As an example of a strategic plan, see U.S. Department of Energy. National Nuclear Security Administration. "Nuclear Explosion Monitoring Research and Engineering Program: Strategic Plan," https://na22.nnsa.doe.gov/ndd/strategicplan.

[112] Personal communication, June 23, 2009. Jeanloz continues, "Interestingly, the question of containment of gases in the Earth's crust is also important for energy and environmental issues such as carbon sequestration. While the time scale is much longer for sequestration (centuries to millenia) than for nuclear explosion monitoring (hours to days), the issue of gas containment in the crust is pretty much the same, and study of long-term sequestration would benefit from a better understanding of short-term containment, such as for CTBT monitoring." Jonathan Katz, Professor of Physics at Washington University in St. Louis, states, "the issues of noble gas seepage and carbon dioxide (CO2) sequestration are not quite the same. Unlike noble gases, CO2 will react with some rocks and ground water, and will liquefy under pressure at room temperature. Both effects make a difference for diffusion." Personal communication, August 4, 2009.

Provide Fellowships

Breakthroughs in analysis could enable seismologists to extract more information from seismic data and lead to improved concepts for future seismic networks.[113] However, such advances, as well as maintaining long-term monitoring capability more generally, will require training of graduate students in nuclear explosion monitoring disciplines. One expert stated,

> The past decade has seen sharp fluctuations in funding of programs in this area by two key sources, the Air Force Research Laboratory and the National Nuclear Security Administration, and funding has been far below the level recommended by a 1997 National Research Council report. Low and erratic funding has disrupted graduate student training. As a result, it is becoming hard to sustain adequate numbers of experts in nuclear explosion monitoring, as evidenced by recent difficulties in replacing seismologists who retired.[114]

To address this issue, the United States could support, at a steady level, fellowships and programs adequate to produce enough experts in nuclear explosion monitoring to meet national needs. Similarly, Congress, in P.L. 111-140, Nuclear Forensics and Attribution Act, found, "The number of radiochemistry programs and radiochemists in United States National Laboratories and universities has dramatically declined over the past several decades."[115] In response, this act would establish a National Nuclear Forensics Expertise Development Program.

Deploy More Monitoring Equipment

Add Radionuclide Stations and Radioxenon Equipment

Since venting or seepage of radioxenons is more likely than venting of particulates, many agree that it would be desirable for the IMS to have radioxenon equipment at all 80 radionuclide stations instead of the 40 currently planned. The treaty (Protocol, paragraph 10) provides for this expansion once it enters into force: "At its first regular meeting, the Conference [of the States Parties] shall consider and decide on a plan for implementing noble gas monitoring capability throughout the network." The CTBTO PrepCom indicates that adding radioxenon equipment to the remaining 40 particulate stations would not be technically difficult, but is more a matter of political will and financial resources.[116] The PrepCom also states, "there has been a strong interest in building up and strengthening the noble gas capability since the 2006 DPRK declared test within the CTBTO PrepCom."[117] The European Union has made voluntary contributions for this purpose,[118] and the United States has made technical contributions to this effort.[119] It may also be

[113] Email from Raymond Jeanloz, Professor of Geophysics, University of California, Berkeley, April 20, 2009.

[114] Information provided by Thorne Lay, Professor of Earth and Planetary Sciences, University of California, Santa Cruz, personal correspondence, April 20, 2009. The 1997 report is Thorne Lay et al., *Research Required to Support Comprehensive Nuclear Test Ban Treaty Monitoring,* National Research Council, National Academies Press, 1997.

[115] H.R. 730 passed the Senate with an amendment by unanimous consent on December 23, 2009. On January 21, 2010, the House agreed to the Senate amendment, 397-10. The President signed the bill into law February 16. 2010.

[116] Personal communications, July 30, 2009, and December 8, 2009.

[117] Personal communication, September 15, 2009.

[118] In 2007 and 2008, the European Union provided a total of €3.986 million, part of which was to be used for noble gas monitoring. See "Council Joint Action 2007/468/CFSP of 28 June 2007," *Official Journal of the European Union,* July 6, 2007, pp. L 176/31-L 176/38; and "Council Joint Action 2008/588/CFSP of 15 July 2008," *Official Journal of the European Union,* July 17, 2008, pp. L 189/28-L 189/35.

[119] Personal communication, NNSA staff, November 20, 2009.

desirable to equip all 80 stations with radioxenon equipment, or to increase the number of radionuclide stations with radioxenon equipment beyond 80, *before* the treaty enters into force. Additional stations in Japan and South Korea, and in areas of China and Russia close to North Korea, would be of particular value for monitoring any testing by that nation.

Procure Mobile Radionuclide Collection Equipment for Rapid Deployment

Even completing the IMS and having radioxenon equipment at all 80 radionuclide stations would leave gaps in coverage, as **Figure 2** shows for North Korea. These gaps pose a problem for monitoring and verification. For example, a test might release radioactive material that wind currents blow away from IMS stations, or the wind might loft such material high above these stations, which are at ground level. Mobile detection systems ready to deploy immediately after detecting a nuclear test would help address this problem. These systems could include ships and radionuclide collection aircraft to deploy on or over international waters, and land-mobile systems to deploy in nations near the suspected test. These systems might or might not be part of the IMS depending on how they were handled pursuant to Article IV (verification), paragraphs 23-25 of the treaty, "Changes to the International Monitoring System." Even if these systems were not included in the IMS, states could still share the resulting data with the International Data Center pursuant to Article IV, paragraphs 27 and 28, "Cooperating National Facilities."

Mobile systems offer many advantages. The ability to collect over broad ocean areas would close some gaps in the IMS. Since mobile systems could collect data close to and soon after a suspected detonation, they might be able to collect particulates before they dropped back to Earth. Particulates can provide high confidence that the material originated from a nuclear test; they can also provide data on certain weapon characteristics. Gathering radioxenons quickly is of particular value for analyzing the ratio of xenon-135 to xenon-133, which can also provide high confidence that a test was nuclear. The rapid decay of xenon-135 (half-life, 9.14 hours), plus the decay of iodine-133 and -135 into xenon-133 and -135, respectively, precludes such analysis after a short time. Close-in, rapid collection should result in higher concentration of radionuclides, facilitating analysis, because they would have less time to dilute in the atmosphere. Hafemeister states that airborne sensors or ground sensors closer to a test can enhance the concentration of radionuclides by a factor of more than a million.[120] Close-in collection should also result in more confident determination of which nation conducted a test by greatly reducing the number of countries from which the radionuclides could have originated.

There could be obstacles to airborne or seaborne collection systems operating on or over international waters. For example, according to press reports, North Korea fired several surface-to-air missiles around the time of the 2009 nuclear test that "appeared to be aimed at keeping U.S. and Japanese surveillance planes away from the nuclear test site."[121]

[120] David Hafemeister, "Input to the NAS CTBT Study," presentation to the CTBT Review Committee of the National Academy of Sciences, September 9, 2009, p. 24.

[121] Jean Lee, "Defying World Powers, N. Korea Conducts N Test," *Associated Press*, May 25, 2009, http://www.breitbart.com/article.php?id=D98DCSF00&show_article=1.

Improve the Capability of Monitoring Systems

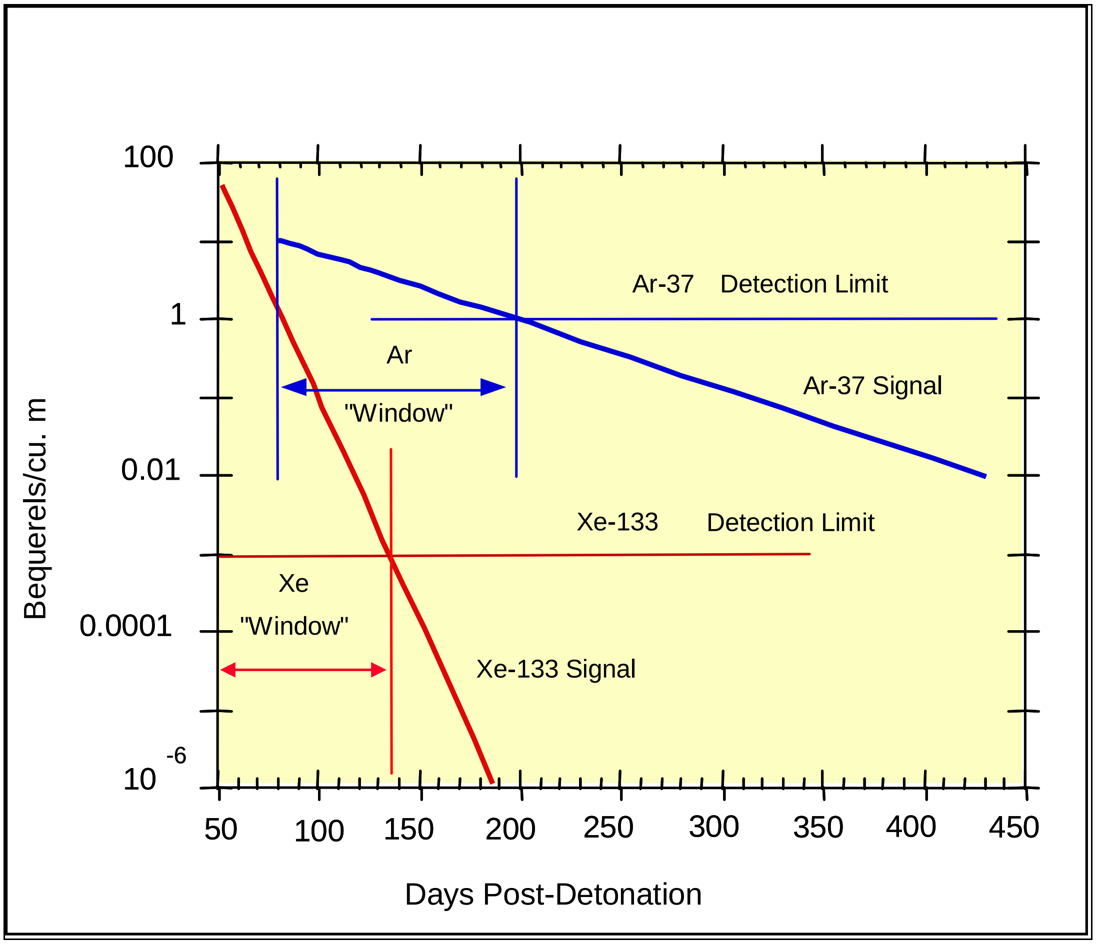
Increase the Sensitivity of Detection Equipment

While the capability to detect radioactive noble gases is very good, it could be improved. So doing would increase the probability of detection, both remote and onsite, by enabling a detector to pick up a signal from a radioisotope at a lower concentration or for a longer time. **Figure 5** illustrates the point for onsite detection. It shows a detection limit or threshold for argon-37 and xenon-133 (horizontal lines). It shows the signal from these two isotopes diminishing over time (diagonal lines), with the xenon signal diminishing faster than the argon signal because the former has a shorter half-life, 5.3 days vs. 34.8 days. The "window," or the period in which an isotope can be detected (vertical lines), opens when the gas reaches the surface, with xenon and argon reaching the surface about 50 and 80 days, respectively, after a detonation as a result of barometric pumping, and closes when the amount of either gas falls below the detection threshold.[122] Thus if the detection threshold can be lowered, the window closes later. While the graph shows the signal as starting out at its peak, in practice the signal would begin at zero and at some point would rise rapidly. As a result, a more sensitive detector might also "open" the window slightly earlier.

[122] Charles Carrigan, "Using OSI Field Studies and Tests to Define Noble Gas Sampling and Analysis Requirements," presentation at INGE [International Noble Gas Experiment] 2009, Daejeon, Korea, November 9-14, 2009, Lawrence Livermore National Laboratory document LLNL-PRES-41961, p. 11. This prediction assumes good test containment and the barometric and geologic conditions present for a specific (nonnuclear) test conducted at the Nevada Test Site. This test, the Non-Proliferation Experiment (NPE), was conducted on September 22, 1993, and used some 1,400 tons of chemical explosive, along with small quantities of gases intended to simulate certain radioactive gases. Other conditions could produce different results. For further information on NPE, see U.S. Department of Energy. *Symposium on the Non-Proliferation Experiment: Results and Implications for Test Ban Treaties*, CONF-9404100, April 19-21, 1994, https://na22.nnsa.doe.gov/cgi-bin/prod/nemre/index.cgi?Page=Symposium+1994.

Figure 5. Detection "Window" for Argon-37 and Xenon-133

Lowering the Detection Limit Keeps "Window" Open Longer



Source: Charles Carrigan, "Using OSI [On-Site Inspection] Field Studies and Tests to Define Noble Gas Sampling and Analysis Requirements," Paper presented at International Noble Gas Experiment-2009 Conference, Daejeon, Korea, November 9-14, 2009, Lawrence Livermore National Laboratory, LLNL-PRES-41961.

Notes: 1 Becquerel = 1 radioactive disintegration per second. Calculations are derived from a model based on data obtained from the Non-Proliferation Experiment (NPE), an underground blast conducted in 1993 at the Nevada Test Site that used nonnuclear explosives to simulate a 1-kiloton nuclear explosion. It used helium-3 gas to simulate argon-37 and sulfur hexafluoride gas to simulate xenon-133.

Study Numbers, Types, and Basing for Aircraft That Collect Nuclear Debris

The Air Force Technical Applications Center (AFTAC) operates two WC-135 "Constant Phoenix" aircraft, which are designed to collect particulates and gases from a nuclear explosion. The WC-135 is a component of the U.S. Atomic Energy Detection System.[123] AFTAC states,

> The Air Force maintains one primary and one backup WC-135 to support airborne nuclear collections. The aircraft are operated by the 55th Wing, 45th Reconnaissance Squadron at

[123] U.S. Air Force. "WC-135 Constant Phoenix," fact sheet, http://www.af.mil/information/factsheets/factsheet.asp?id=192.

> Offutt Air Force Base, Neb. Both the primary and backup aircraft are equipped with an AFTAC collection suite that provides the capability to collect the gaseous and particulate debris that might be released from a nuclear explosion. The Air Force is conducting an Analysis of Alternatives to determine solutions that can support changing mission requirements and will provide long term, viable alternatives to the current capability as it reaches end of life (the WC-135 airframes are almost 50 years old).[124]

The Air Force elaborated on the preceding statement: "Currently, the WC-135 must be evaluated for re-skinning the wings in around 2022, and AFMC [Air Force Materiel Command] asserts TF-33 engine sustainment through 2040. Otherwise, there is not an explicit end-of-life date." The analysis of alternatives "will examine the WC-135, plus other manned and unmanned aircraft, and assess the number of each aircraft appropriate for the mission."[125]

One of the two WC-135s is the primary aircraft; the other is a backup. The Air Force stated, "Either aircraft can fly the mission. Also both aircraft can be flown simultaneously. However, one of the aircraft is usually in Primary Depot Maintenance (PDM) and therefore would be unavailable. If both aircraft are out of PDM then they both can support mission."[126] Thus the USAEDS airborne collection asset at most times is a single aircraft nearly 50 years old based thousands of miles from North Korea and also from Iran.

Given the prospect that several nations, over a vast geographic area, might conduct nuclear tests, it would be of value to collect samples as soon as possible to narrow the region where the test occurred, to minimize the loss of samples with time, and to have a chance of obtaining samples of xenon isotopes with forensic value. Accordingly, it may be desirable to have more than two aircraft for this purpose, and to have some forward-based. Forward basing might be less costly for large, long-range Reaper- or Global Hawk-type drones than for WC-135s and similar aircraft.[127] For example, since these drones are remotely operated, personnel controlling the mission and operating the sensors (as distinct from the ground crew) would not have to be forward-based. Also at issue is whether to extend the service life of WC-135s or procure new aircraft. Finally, it may be worth considering whether to add airborne sensors to the IMS, which would have to be done in accordance with Article IV, paragraphs 11 and 23, of the CTBT.

Congress is aware of the importance of collecting samples promptly. In the Nuclear Forensics and Attribution Act, it found,

[124] Information provided by Air Force Technical Applications Center through Air Force Legislative Liaison Office, email, October 26, 2009.

[125] Information provided by Air Force Legislative Liaison Office, email, October 29, 2009.

[126] Information provided by U.S. Air Force Legislative Liaison Office, November 24, 2009.

[127] The MQ-9 Reaper is a large remotely-piloted aircraft designed for ground attack or intelligence missions. Several characteristics may make it suitable for collecting radionuclide samples. Its range is 3,682 miles, its payload is 3,750 pounds, its ceiling is up to 50,000 feet, it has long endurance, and it can be loaded into a container for deployment by aircraft, e.g., C-130 Hercules, worldwide. U.S. Air Force. "MQ-9 Reaper," fact sheet, http://www.af.mil/information/factsheets/factsheet.asp?id=6405. The RQ-4 Global Hawk might also be used to collect radionuclide samples. Its mission is long-range high-altitude intelligence, surveillance, and reconnaissance. It is larger than the Reaper, has a range of 10,939 miles, a payload of 2,000 or 3,000 pounds, depending on the model, and a ceiling of 60,000 feet. U.S. Air Force. "RQ-4 Global Hawk," fact sheet, http://www.af.mil/information/factsheets/factsheet.asp?id=13225. By way of contrast, the Predator has a range of 454 miles, a payload of 450 pounds, and a ceiling of 25,000 feet. U.S. Air Force. "MQ-1 Predator," fact sheet, http://www.af.mil/information/factsheets/factsheet.asp?fsID=122.

> Many of the radioisotopes produced in the detonation of a nuclear device have short half-lives, so the timely acquisition of samples is of the utmost importance. Over the past several decades, the ability of the United States to gather atmospheric samples—often the preferred method of sample acquisition—has diminished. This ability must be restored and modern technologies that could complement or replace existing techniques should be pursued.

Improve Onsite Inspection Capability

Since the previous administration did not seek entry into force of the CTBT but did favor improving means of monitoring nuclear testing, it requested only those funds for the CTBTO Preparatory Commission that directly supported the IMS. It requested these funds in the State Department's International Affairs Function 150 budget in the Nonproliferation, Antiterrorism, Demining, and Related Programs account. The FY2007 budget justification, for example, stated that the requested funds, $19.8 million, would "pay the U.S. share for the ongoing development and implementation of the International Monitoring System (IMS), which supplements U.S. capabilities to detect nuclear explosions. Since the United States does not seek ratification and entry-into-force of the CTBT, none of the funds will support Preparatory Commission activities that are not related to the IMS."[128] While the PrepCom budget shows no nation-by-nation link between funds received and funds spent, this quotation illustrates the attitude toward expenditures that would be of value only if the CTBT were to enter into force, such as OSIs. Consistent with this policy, the administration directed U.S. R&D funding away from OSI issues and toward IMS technologies.

With the Obama Administration favoring the CTBT, and with OSIs a key part of the verification regime, more might be done to make them more effective. One approach would be to develop more sensitive detectors. A second would be to integrate geophysical methods for detecting anomalies hundreds of feet underground with gas sampling techniques to help inspectors locate a suspected test more precisely. A third would be to conduct field experiments on how noble gases reach the surface. The only OSI-type gas sampling experiment was performed in conjunction with the 1993 NPE (see "Increase the Sensitivity of Detection Equipment"). Conducting similar experiments (perhaps releasing gases in mine shafts to reduce costs) under various geologic, containment, hydrologic, and barometric conditions would help develop and calibrate computer models of gas leakage from underground tests, making results of the type found in 1993 applicable to a wider range of conditions under which OSIs might be conducted.

Conduct Further R&D on Satellite Detection

Given the immense value of data provided by satellites, Congress might explore whether additional R&D might be warranted on satellite-borne means of detecting signatures that a clandestine nuclear program or test, or preparations for a nuclear test, might produce. While the IMS does not include satellites, the Provisional Technical Secretariat, which operates the IMS, might want to conduct such R&D as well, both because it can utilize commercial satellite imagery and because the IMS might, at some point, have access to its own satellite data. The CTBT provides (Article IV, paragraphs 11 and 23) for the possibility of adding monitoring technologies such as satellites to the IMS if agreed pursuant to Article VII (Amendments).

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[128] U.S. Department of State. *Summary and Highlights: International Affairs Function 150, Fiscal Year 2007 Budget Request*, p. 40, at http://www.state.gov/documents/organization/60297.pdf.

Evaluate Classified Projects

The United States is presumably conducting classified R&D in areas related to the subject matter of this report. The relevant congressional committees may wish to determine what efforts, if any, are being made along these lines and whether the level of effort in each such area is appropriate. For example, many evasion scenarios set forth by CTBT opponents were created decades ago, some in the 1950s. They have been studied and debated ever since, and study of such scenarios remains a daily concern of the Intelligence Community. The ability to defeat evasive scenarios would increase confidence in detection capability, while an inability to defeat them would help guide detection R&D. Either way, efforts to develop and to defeat these scenarios would challenge scientists working on detection, just as with any other offense-defense competition. However, few new evasion scenarios or technologies appear in the public record out of concern that public discussion of them could aid would-be evaders.

Look for New Signatures to Help Determine If a Test Is Nuclear

Examine Costs and Benefits of Long-Range Detection of Argon-37

As noted earlier, it may be feasible and useful to detect argon-37 at a distance. However, moving from "may be feasible" to an operational system would require characterizing background levels of this isotope; determining the value that might be gained by detecting this isotope in addition to detecting xenon-133; studying the worldwide distribution of calcium, especially at likely test sites; developing automated detection equipment that could be used at remote locations, such as at IMS radionuclide stations; and determining whether the cost of this effort is worth the benefit.

Study Signatures of a Chemical Explosion

As the case of the 2009 North Korean test shows, it would be useful to determine if an explosion was nuclear or chemical in order to reveal if a nation had conducted a nuclear test or was bluffing. Effluents of a chemical explosion would probably not permit making that determination because they would be hydrocarbons and there is a huge atmospheric background of such materials from vehicles, industry, forest fires, mining explosions, etc. However, there might be other signatures, such as in the preparation, seismic waves, or post-event activity. For example, detailed study of seismic waves might reveal slight differences between those generated by nuclear or chemical explosions. This was a goal of the 1993 NPE, though the apparent inability to prove conclusively that the 2009 North Korean event was or was not nuclear indicates that more work along these lines may be warranted. At the same time, it would be important to guard against the prospect that a nation could create signatures of a chemical explosion as cover for a nuclear test. The ability to monitor signatures of nonnuclear explosions is especially important in situations like the 2009 event prior to CTBT entry into force. After entry into force, should it occur, onsite inspections would be available to help resolve such situations.

Author Contact Information

Jonathan Medalia
Specialist in Nuclear Weapons Policy
jmedalia@crs.loc.gov, 7-7632