National Academy of Sciences Study on the Comprehensive Nuclear Test Ban Treaty

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After the 51-48 defeat of the CTBT in the Senate, the National Academy of Sciences was commissioned by General John Schalikashvili (Former Chair, Joint Chiefs of Staff) to examine technical issues relating to the CTBT. The issues reviewed in this paper are as follows:

Verification: Seismic monitoring of tamped, underground nuclear explosions with the International Monitoring System is better than what was originally stated (1 kton), to about 0.1 kton. When the NAS panel took all the factors into account by the NAS, muffled explosions detonated in cavities can be detected down to 1~2 kton. The advent of interferometric synthetic aperture radar compliments the CTBT monitoring technologies (seismic, infrasound, hydroacoustic, radionuclide) and NTM methods by measuring surface subsidence to 0.1 cm.

Stockpile Stewardship: All scientific review groups agree that nuclear testing is not needed at this time, and the NAS concludes that it is unlikely to be needed in the future. Plutonium decay in the primary stage does not greatly limit the Pu pit lifetime, which NNSA determined to be a minimum of 45~60 years. The most likely weapon components to suffer degradation are the non-nuclear components, which can be monitored without the need of nuclear testing.

Benefits of Cheating: After an evaluation of the weapons programs of other nations, the NAS concluded that “Very little of the benefit of a scrupulously observed CTBT regime would be lost in the case of clandestine testing within the considerable constraints imposed by the available monitoring capabilities… The worst-case scenario under a no-CTBT regime poses far bigger threats to U.S. security - sophisticated nuclear weapons in the hands of many, more adversaries - than the worse-case scenario of clandestine testing in a CTBT regime, without the constraints posed by the monitoring system.”

1. CTBT in Context

Building on the experience of three previous nuclear testing treaties (1), the Comprehensive Test Ban Treaty (CTBT) bans all nuclear tests of any yield in all places for all time. This requires the fulfillment of complete bans in terms of four parameters (number, yield, location and time). The CTBT is an arms control measure that constrains the five nuclear weapons states from developing new weapons. In the past, the US tested the most at 1,030 times, followed by the Former Soviet Union with 715 tests, which is much more than the tests of other states; France (210), UK (45) and China (45), as well as India and Pakistan at about five each. The CTBT is also a nonproliferation measure since the test ban raises a barrier to the development of first-time nuclear weapons. The 1998 tests by non-NPT (Nuclear Nonproliferation Treaty) parties, India and Pakistan, highlighted the need for a universally accepted CTBT and NPT. The CTBT also affects the long-term stability of the NPT. The agreement by the five nuclear weapon states (China, France, RF, UK, US) to join the CTBT was the quid pro quo accepted by the five nuclear weapon states in 1996 to gain the acceptance by 183 non-nuclear weapon states to extend the NPT for all time. The Council of the American Physical Society approved statements strongly supporting the CTBT on April 19, 1997 and April 4, 2003 (2).

The CTBT has been signed by 169 nations (December 2003), which amounts to all the nuclear capable nations, except for India, Iraq, and Pakistan (North Korea has announced that it possesses nuclear weapons and it has been widely reported that Israel also has a stock). Of the signatory nations, 107 have ratified the CTBT, including three nuclear weapons states (Russia, France, United Kingdom). In October 1999, the US Senate rejected the CTBT by a vote of 51 to 48. (China stated it will ratify the CTBT only after the US ratifies it.) After the defeat of the CTBT, the National Academy of Sciences was asked by the Clinton administration to convene a panel of experts (3) to examine technical issues that could affect the viability of a test ban. The results of the NAS study, Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty, were published in 2002 (4). The Academy decided early on not to evaluate the net benefit of the CTBT to the United States, but rather the NAS examined the following three technical issues:

- ability to monitor a test ban, including evasion scenarios.
- US capacity to maintain a safe and reliable nuclear stockpile without testing.
- ability of nations to increase nuclear prowess by cheating and its effect on US security.

NPT-CTBT Connection. As stated above, the non-nuclear weapons states view the CTBT as the quid pro quo that fulfills the requirement of the five nuclear weapons states to balance their CTBT obligations to the 183 non-nuclear weapon states. This balancing act was very apparent to the 5 nuclear weapon states in 1996. The NPT would not have been renewed by the 183 states for all time, without a time limit, unless all five nuclear weapon states declared they would join the CTBT. The continuation of the NPT is of fundamental importance to all nations, as it is the legal capstone that constrains the nuclear rogue states (President Clinton) and the axis of evil (President George W. Bush). On December 8, 2003 the General Assembly of the United Nations passed a resolution that urged all nations to maintain the nuclear testing moratorium, urged all nations to sign the CTBT and urged all nations that had signed the CTBT to ratify it. The gap between the US and the rest of the world could not be more apparent from the following. The vote in the General Assembly was 173 in favor, 1 against (U.S.) and four abstentions (Columbia, India, Mauritius, Syria), while Iraq and North Korea were absent. The intensity of the global diplomatic opinion on the CTBT/NPT connection is not understood by the US populace.

2. Monitoring the CTBT

The Senate debate on the CTBT was marred by claims that cheating could take place without detection at yields up to 70 kilotons. The NAS report strongly contradicts this claim. The CTBT Organization's International Monitoring System (IMS) deploys 300 monitoring stations that use seismic, hydroacoustic, radionuclide, or infrasound sensors. These facilities are operating today without the CTBT having entered into force. The IMS network consists of 50 primary and 120 auxiliary seismic stations. In addition the IMS deploys 60 infrasound stations (less than 0.5-kton global atmospheric threshold detection), 11 hydroacoustic stations (less than 100-kg global oceanic detection) and 80 radionuclide stations (less than 1-kton, global atmospheric detection). In addition, the US uses satellite optical bhangmeters, particle detectors and EMP detectors to monitor atmospheric tests. Lastly, US National Technical Means (NTM) monitors with other technologies, including satellite reconnaissance, human intelligence (humint) and other "ints." The IMS and NTM technologies combine to make intelligence gathering a synergistic operation that is greater than the sum of its parts. The fear of being spotted by the IMS and NTM deters most nations from cheating, and these measures will be buttressed by on-site inspections. Since the signing of the CTBT, a potent new technology, interferometric synthetic aperture radar (ISAR), has been disclosed, which we will discuss at the end of this section.

The US, Russia and UK have only tested in underground locations since 1963, and they have been joined in this by France (1974), China (1980), India (1974, 1998) and Pakistan (1998). Seismographs are the primary tool for monitoring underground tests, with the other technologies supplementing this data. Seismic traces from nuclear explosions differ from earthquake traces in several ways. Nuclear explosion seismic data have higher-frequency components than those from earthquakes because the duration of an explosion is much shorter than the duration of an earthquake. In addition, the ratio of the short-period, pressure body wave magnitude (mb) to the long-period, surface wave magnitude (MS), is larger for weapons than for earthquakes. The zero-threshold limit for the CTBT was chosen because a finite limit legalizes testing below that limit and because accurately determining a threshold adds a source of error (5).

The International Monitoring System (IMS) has the capability to detect explosions with high confidence (90% certainty) to an mb level of 3 (less than 2.5 for Russia's Novaya Zemlya), which corresponds to a tamped explosion of about 0.1 kton in hard rock throughout Eurasia and North Africa. The contours in Fig. 1 are in tons (not kilotons). These results are from the Defense Department's Center for Monitoring Research, which agrees with calculations from the national laboratories and universities. The limit of 0.1 kton for tamped explosions is a factor of ten better than the 1 kton limit that was originally projected for the IMS. Even this estimate can be too cautious in that it does not take into account the possibility of close-in, regional stations. A concerned state could place regional seismographs close to a suspected region to improve monitoring. Finally, chemical explosions are usually identifiable as they are not spherical explosions, but they are often ripple-fired along a line to reduce costs. The required notification threshold for chemical explosions is 0.3 kton, which reduces suspicions about chemical explosions.

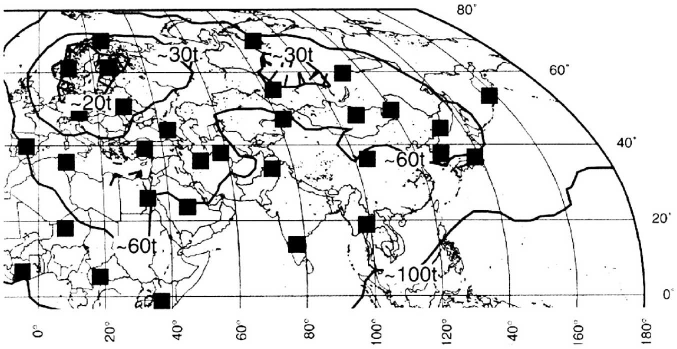

Fig. 1. IMS seismic monitoring limit (tons). Projected 90%-probable, 3-station detection thresholds in tons of explosive yield for the IMS network of 50 primary stations. The IMS detection threshold is below 0.1 kton for all of Eurasia and below 0.5 kton for all continents worldwide. The 1999 IMS system with 33 stations detected 0.1 kton underground chemical explosions and a 0.025-kton explosion at the former Soviet Semipalatinsk test site in Kazakhstan. [Center for Monitoring Research, Nuclear Testing Programs, Department of Defense, in Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty, National Academy of Sciences, National Academy Press, 2002]

Explosion in a Cavity. There are very little data on nuclear tests exploded in cavities. If a nuclear weapon is placed in a cavity of sufficient size, the blast pressure on the cavity wall falls below the material's elastic limit, which avoids cracking and nonlinear effects, reducing the effective seismic yield by a theoretical factor of 7 at 20 Hz and 70 at lower frequencies. The only fully decoupled test took place in 1966 when the 0.38-kton Sterling explosion was exploded in a Mississippi salt cavity with a 17-m radius (from the 5.3-kton, Salmon explosion); it minimized the observed yield by, at most, a factor of 70. The Soviets carried out a 9-kton test in a cavity at Azgir in 1976, but it was only partially decoupled, as the weapon was too large for the cavity's 36-m radius (from a 64-kton previous test).

If blast pressure exceeds the elastic limit of the cavity's wall material, sufficient energy is absorbed to crack the wall, increasing coupling to the wall, giving an increased seismic signal. Critical cavity size depends on explosion depth, but it is usually assumed to be about 1 km. One expects that R_c is proportional to $Y^{1/3}$ since the energy to fill the volume of the cavity to a critical pressure is proportional to the yield, or $Y \alpha$

$P\Delta V \propto R_c^3$. The *critical radius for decoupling* increases with yield to the third power, according to

$$R_c = (15\text{–}20 \text{ meters})Y^{1/3},$$

with Y in kton. From this, a 70-kton explosion needs a cavity radius of 70 m (a 20-story building) to achieve full decoupling – an extraordinary engineering challenge when one considers the secrecy requirements.

We derive the coupling constant from first principles for a 1-kton blast in salt. Because explosion occurs very rapidly, little heat is transferred during the compression. This dictates an adiabatic expansion with $PV^{\gamma} = C$, a constant. The yield Y to compress air to the elastic limit of salt is

$$Y = -P\,dV = -CV^{-\gamma}\,dV = CV^{1-\gamma}/(\gamma - 1) = P_o(4\pi R_c^3/3)/(\gamma - 1) = P_oV_c/(\gamma - 1),$$

where P_o is the elastic limit of the wall material and V_c is minimum cavity volume.. Using Y = 1 kton, $\gamma = = 1.2$ (very hot air) and $P_o = 440$ bar for salt's elastic limit, we obtain the minimum cavity radius $R_c = 16$ m. The critical radius is 30 m at a depth of 600 m (6).

Monitoring Limit with Cheating. The NAS panel concluded that "The only evasion scenarios that need to be taken seriously at this time are cavity decoupling and mine masking." The NAS panel considered many issues that affect the probability of successfully hiding a nuclear test in a cavity. For example, covert testing is complicated by the possibility of venting of radioactive gases from the explosion, which can easily be detected. The Soviets had 30% of its tests vent, and the US had severe venting problems during its first decade of underground testing. Venting from smaller tests is often harder to contain than venting from larger ones, as the last four US tests that vented had yields of less than 20 kilotons. This tendency to vent at lower yields can be explained by the hypothesis that smaller explosions may not sufficiently enclose cavities with glassified rubble, and they may not rebound sufficiently to seal fractures with a stress cage. The NAS panel considered six other issues as follows:

- Violators need to make accurate yield estimates to avoid yield excursions.
- Violators need to hide removed materials from satellites.
- Crater and surface changes from testing are observable.
- Regional seismic signals at 10 Hz improve detection.
- A series of tests is needed to develop significant weapons.
- Human and other intelligence can give information.

Because the total success probability for hiding a covert test is the product of the individual-task success ($P_{success} = \Pi_i P_I$), the NAS panel did not use a decoupling factor of 70 times the 0.1-kton limit to obtain a maximum cheating limit of 7 kton. Rather, it concluded the following: "Taking all these factors into account and assuming a fully functional IMS, we judge that an underground nuclear explosion cannot be confidently hidden if the yield is larger than 1 or 2 kton."

Interferometric Synthetic Aperture Radar. Signatures from underground nuclear tests can be obtained using accurate satellite radar interferometry (7). By combining synthetic aperture radar data (European Space Agency) from before and after a nuclear test, crater subsidences as small as 0.1 cm can be measured. The radar data has a horizontal resolution of better than 10 m, which is much smaller than a typical crater subsidence radius of about 100 m. A typical radar frame covers 100 km by 100 km, sufficient to search wide areas. The ISAR data can also determine the slow subsidence relaxation over longer times. This allows ISAR to locate past explosion locations for which there was no radar data prior to the explosion. Interferometric radar has some limitations, but it is a very positive addition to CTBT monitoring.

3. Stockpile Stewardship

The NAS panel examined many factors in its analysis on the US ability to maintain a safe and reliable nuclear weapon stockpile without testing:

- Confidence requires a high-quality workforce and adequate budgets.
- Stockpile stewardship and enhanced surveillance must examine components of weapons.
- Remanufacture to original specifications is the preferred remedy for age-related defects.
- A highly disciplined process is needed to install changes in nuclear designs.
- Primary yield that falls below the minimum level needed to drive a secondary is the most likely potential source of nuclear-related degradation.
- Based on past experience, the majority of aging problems will be found in the non-nuclear components, which can be fully tested under a CTBT. (NNS has stated that nuclear Pu pits have a minimum lifetime of 45-60 years with "no life-limiting factors.")
- In the past, confidence tests were limited to one per year, as most tests were carried out to critique new designs.
- New stewardship programs, using the Dual Axis Radiographic Hydro Test (DAHT) facility and Advanced Simulation and Computing (ASC), are already valuable

During the technical briefings, potential problems for existing warheads (8) in the enduring stockpile were raised. The NNSA was asked if testing was needed to resolve these issues and the answer was always "no". From all of these results, the Academy panel concluded the following:

"Although a properly focused stockpile stewardship program is capable, in our judgement, of maintaining the required confidence in the enduring stockpile under a CTBT, we do not believe that it will lead to a capability to certify new nuclear subsystem design for entry in the stockpile without nuclear testing – unless by accepting a substantial reduction in the confidence in weapon performance associated with the certification up until now, or a return to earlier, simpler, single stage design concepts such as gun-type weapons."

"It seems to us that the argument to the contrary – that is, the argument that improvements in the capabilities that underpin confidence in the absence of nuclear testing will inevitably lose the race with the growing needs from an aging stockpile – underestimates the current capability for stockpile stewardship, underestimates the effects of current and likely future rates of progress in improving these capabilities, and overestimates the role that nuclear testing ever played (or would be ever likely to play) in ensuring stockpile reliability."

4. NAS Conclusion on Potential Impact of Foreign Testing

Section 2 of this paper showed that explosions of tamped weapons can be detected with high confidence in Eurasia for yields over 0.1 kton, and explosions in a cavity can be detected above 1–2 kton. What can nations learn from cheating at these levels? Nations with lesser prior-testing experience can carry out equation of state studies, high-explosive lens experiments, certification of bulky inefficient unboosted fission weapons (gun-type), one-point safety tests, limited improvement of unboosted fission weapons, proof tests of compact weapons with yields up to 1–2 kton (with difficulty and without an excursive yield). Nations with greater prior-testing nuclear test experience could partially develop primaries for thermonuclear weapons. The CTBT prevents the development of low-yield boosted fission weapons, and the full testing of primaries (over 1–2 kton) and thermonuclear weapons. The NAS study commented on what Russia, China and other nations could gain from cheating on a country-by-country basis.

Of course cheating on the CTBT would be a blow to the political aspects of the nonproliferation regime. However, the NAS panel concluded the following: "But potential undetected Russian and Chinese evasive testing is not relevant to the maintenance of US nuclear weaponry. As noted in Chapter 1 (on stockpile stewardship), we judge that the United States has the technical capability to maintain the reliability of its existing stockpile without testing, irrespective of whether Russia or China decides they need to test in order to maintain the reliability of theirs…."

"Very little of the benefit of a scrupulously observed CTBT regime would be lost in the case of clandestine testing within the considerable constraints imposed by the available monitoring capabilities. Those countries that are best able to successfully conduct such clandestine testing already possess advanced nuclear weapons of a number of types and could add little, with additional testing, to the threats they already pose or can pose to the United States. Countries of lesser nuclear test experience and design sophistication would be unable to conceal tests in the numbers and yield required to master nuclear weapons more advanced than the ones they could develop and deploy without any testing at all."

"The worst-case scenario under a no-CTBT regime poses far bigger threats to U.S. security – sophisticated nuclear weapons in the hands of many more adversaries – than the worse-case scenario of clandestine testing in a CTBT regime, without the constraints posed by the monitoring system."

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(Endnotes)

[1] The Limited Test Ban Treaty, entered into force (EIF) in 1963, bans nuclear tests in the atmosphere, outer space and under water. The Threshold Test Ban Treaty bans underground nuclear tests of over 150 kilotons. Its 1988 protocol added on-site inspections (OSI). (Signed 1974, EIF 1990.) The Peaceful Nuclear Explosions Treaty limits PNEs to underground explosions to a maximum of 150 kton for individual PNEs and 1500 kton for group explosions. (Signed 1976, EIF 1990.)

[2] http://www.aps.org/statements/index.cfm

[3] J. Holdren (chair), H. Agnew, R. Garwin, R. Jeanloz, S. Keeny, C. Larson, A. Narath, W. Panofksy, P. Richards, S. Sack, A. Trivelpiece with staff of J. Husbands and D. Hafemeister.

[4] Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty, National Academy Press, Washington, DC, 2002. Further details can be found in D. Hafemeister, *Physics of Societal Issues*, Springer Verlag and AIP Press, New York, 2004.

[5] Monitoring the 150-kton threshold yield of the TTBT was complicated by geological differences in the US and USSR tectonic plates at the test sites. The magnitude of a body pressure-wave seismic wave is

$$m_b = a + b + c \log Y,$$

where m_b is the magnitude of a 1-Hz body wave, a is the 4.1 magnitude of a 1-kton explosion, b is the bias correction for a test site, c is the slope of 0.74 and Y is the yield in kton. A 150-kton yield at the Nevada Test Site has an m_b of

$$m_b = 4.1 + 0.74 \log 150 = 4.1 + 1.61 = 5.71,$$

while a 150-kton explosion at the Soviet site with a bias of 0.4 is 6.11. The US initially and incorrectly assumed there was no bias between the two sites (b = 0), which gave a false impression that a Soviet explosion at 6.11 mb was a violation with

$$Y = 10^{[(6.11 - 4.1 - 0)/0.74]} = 520 \text{ kton}.$$

Later a value of b = 0.2 was used, but this was also too low. The incorrect designation of "likely violation" on Soviet compliance to the TTBT greatly hindered negotiations on the CTBT.

[6] L. Sykes, Public Interest Report 53, no. 3, Fed. Amer. Sci., Washington, DC, www.fas.org/faspir/v53n3.htm

[7] P. Vincent, et al, Geophysical Research Letters, 30, 2141 (2003).

[8] B61/B83 (bombs), W80 (cruise missiles), W62/W78/W87 (ICBMs) and W76/W88 (SLBMs).

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