Verifying a Nuclear Test Ban: Technical Requirements and National Security Implications of Lower Thresholds

Presented
by

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Since the late 1950s six presidents -- from Eisenhower to Carter -- have sought a Comprehensive Test Ban (CTB). Throughout this period a CTB has eluded policy makers in large measure because of a failure to achieve adequate verification measures. In this the twenty-fifth anniversary of the Limited Test Ban Treaty (LTBT) we are once again witnessing a strong public and political demand to stop nuclear weapons testing. Despite the Reagan Administration's efforts to push a test ban as far into the future as possible, over the past three years several scientific and political achievements have moved us prehaps closer to a test ban than we have ever been since the dawn of the nuclear era. General Secretary Gorbachev, by unilaterally halting testing for 19 months, has made it clear that the Soviet call for a test ban is not propaganda, but a high priority political objective. Gorbachev, upon resuming the Soviet testing program in February 1987, indicated that the Soviets would again stop testing if the U.S. would do likewise. On four occasions, beginning in the fall of 1986, the House of Representatives has voted overwhelmingly to join with the Soviets in a moratorium on all testing above one kiloton (kt). The Senate, siding with the Administration, has defeated a similar proposal.

In July 1986, in a joint program with the Soviet Academy of Scientists, the Natural Resources Defense Council (NRDC) began installing seismic monitoring stations around the Soviet nuclear test site. This represented the first time American scientists had been permitted in the Soviet Union for arms control verification. This breakthrough has revolutionized the verification possibilities in all arms control arenas. The NRDC and the Soviet Academy have expanded the network in the Soviet Union to four stations (at Obninsk, Kislovodsk, Arti and Garm), and a fifth (at Irkutsk) should be operable by the end of the year. Expanding on the NRDC work, Incorporated Research Institutes for Seismology (IRIS) is currently negotiating with the Soviet Academy to install 20 high performance seismic stations in the Soviet Union over the next three years.

On September 17, 1987 the U.S. and Soviet Union agreed to resume negotiations on testing, with the first step being to seek more effective measures for verifying the TTBT, leading toward U.S. ratification of the TTBT and PNET, and then to "proceed to negotiate further limitations on testing, leading to the ultimate objective of the complete cessation of nuclear testing, as part of an effective disarmament process." To improve the verification of the TTBT the United States has insisted on being permitted to measure the yield of all Soviet tests over 50 kt using an on-site hydrodynamic system called CORRTEX. To permit the demonstration of this technique and its procedural requirements, the U.S. and Soviet Union, on August 17 and September 14, 1988, conducted a Joint Verification Experiment (JVE), nuclear explosions at their respective test sites in Nevada and Kazakhstan instrumented so that each side could measure the yield of the two tests with their respective hydrodynamic techniques. The success of the JVE should lead to an early resolution of outstanding TTBT verification issues, and hence, ratification by the U.S. of the TTBT and PNET. By agreement the U.S. and Soviet Union should then begin negotiating a reduction of the 150 kt limit and/or quotas on the number of tests.

Regardless of who is elected on November 8, we are likely to see further limits placed on testing during the next Administration. These new test limitations must in part be determined by the effectiveness of verification measures, and how the new Administration assesses the desirability of continued testing. My remarks will focus on an analysis of what verification requirements are necessary for a Low Threshold Test Ban Treaty (LTTBT), or CTB. But first I will review current test limitations.

Current Testing Limits

The United States and the Soviet Union are signatories of the 1963 LTBT, the 1974 Threshold Test Ban Treaty (TTBT), and the 1976 Peaceful Nuclear Explosion Treaty (PNET). Although the TTBT and the PNET have not received the consent of the U.S. Senate and thus have not yet been ratified, both nations consider themselves obligated to adhere to it. The combined effect of these three treaties is to limit the location and size of individual nuclear explosions, namely requiring them to take place underground with individual shot yields limited to 150 kiloton (kt), or less.

There has been debate within the U.S. regarding whether the Soviet Union has been in compliance with the LTBT and the TTBT. The question of LTBT compliance relates solely to venting of radioactive materials from underground tests. The LTBT calls on parties to the treaty to insure that radioactive debris from underground explosions is not vented so as to be dispersed outside of their territorial limits. With regard to TTBT compliance the Reagan Administration has claimed that a number of Soviet tests "constitute a likely violation of the TTBT [150 kt yield limit]." This claim is demonstrably false. As indicated in the OTA's report, Seismic Verification of Nuclear Testing Treaties, May 1988, p. 19:[1]

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[1] See also, Dan M. Davis and Lynn Sykes, "New Estimates of Soviet Nuclear Weapons," Sept 6, 1988, preprint, submitted for publication.

> Extensive statistical studies have examined the distribution of estimated yields of explosions at the Soviet test sites. **These studies have concluded that the Soviets are observing a yield limit consistent with compliance with the 150 kt limit of the Threshold Test Ban Treaty.**

New Testing Thresholds

Christopher Paine, an aide to Senator Kennedy on nuclear testing matters, has given considerable attention to a phased plan to reduce test yields. Based on his analysis there are several logical low yield thresholds based on different objectives. The different yield thresholds and their objectives are given in Table 1.

Currently, the principal means of identifying underground nuclear tests and verifying the size of their yields is the use of seismic monitoring. As the yield threshold is lowered, other techniques, including on-site inspections, satellite photographic intelligence (PHOTINT), signals and human intelligence (SIGINT and HUMINT) would become more important.

The most thorough review of seismic verification requirements for an LTTBT is the OTA study mentioned above. According to the OTA report (p. 14):

> Nuclear tests with explosive yields above 10 kt can be readily monitored with high confidence. This can be done with external seismic networks and other national technical means.

An adequate external seismic network surrounding the Soviet Union already exists, thus, a TTBT as low as 10 kt could be adequately verified today with systems that are currently in place.

To determine the verification requirements for lower threshold levels, e.g. those in Table 1, consideration must be given to possible evasion scenarios. In this regard three major scenarios have been postulated as potential means of evading a LTTBT or CTB. These are:

(a) muffling the sound of the explosion by detonating the device in a large underground cavity, the so-called decoupling scenario;
(b) disguising the nuclear explosion, perhaps decoupled, as an industrial explosion; and
(c) hiding the explosion signal in the coda of an earthquake.

Only (a) and (b) deserve serious attention. As noted by OTA (p. 11) scenario (c), the hide-in-earthquake scenario, is no longer viewed as credible because it is not practical for the evader to wait for an earthquake that is in the immediate vicinity of the test site. When the nuclear test site is at some distance from the earthquake, discrimination is also possible by analyzing the frequency spectra of the digitally recorded seismic signals of modern broad band seismic stations. By filtering out the low frequencies the richer high frequency spectrum of an explosion can be detected and discriminated from the spectrum of an earthquake. With this background we are now in a position to examine separately the rationale and verification requirements for the three threshold levels identified in Table 1.

5-10 Kiloton Threshold

High yield thermonuclear weapons are two-stage thermonuclear designs consisting of a low-yield boosted fission primary and a high yield fusion secondary. In modern U.S. strategic warheads the yields of the primaries are typically in the 5-20 kt range, as evidenced by the distribution of explosive yields of U.S. tests, which peaks between 10 and 15 kt (Figure 1). The analyses of Lynn Sykes and collaborators suggests the yield distribution of Soviet primaries is probably around 20 kt (Figure 2).[2]

It is well known that nuclear warheads can be tested at reduced yields by removal (or substitution) of selected fissile and/or fusion isotopes in the warhead. Some have suggested that a warhead can be adequately tested for certification and introduction into the stockpile provided it can be tested at one-half to one-third the design yield, although there is no consensus on this point among experts.[3] Perhaps under a low-yield threshold the weaponeers might become a little more adventurous and test at one-fifth of the design yield Opinions vary with how well proven is the design. Also, there are some obvious exceptions, e.g., testing boosted devices near 1 kt. To be conservative, however, I will assume that the 5:1 rule of thumb holds and applies to both the primaries and secondaries. Under this assumption, if the testing threshold is established in the 5-10 kt range, new warhead designs with yields above about 25-50 kt could not be certified for introduction into the U.S. stockpile. Reliability tests of primaries of thermonuclear warheads would be possible, some at full yield and the remainder at partial yield. Weapons effects tests, some of which are

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[2] See, for example, Lynn R. Sykes and Steven Ruggi, "Soviet Nuclear Testing," which appears as Chapter 10 of Thomas B. Cochran, et al., Nuclear Weapons Databook, Volume 4, Soviet Nuclear Weapons, (Ballinger Publ. Co.: 1989), in press.

[3] Davis and Sykes, op. cit.

larger than 2 kt to achieve the desired x-ray spectrum, would not be constrained in any significant way.

With regard to verification requirements below 10 kt, consideration must be given to the decoupling evasion scenario. I personally do not think the decoupling evasion scenario represents a serious threat because of the difficulty of avoiding detection by non-seismic means, but in this threshold regime we can rely on seismic techniques alone.

To fully decouple a 5 kt nuclear explosion in salt, a spherical cavity with a radius of at least 43 meters would be required; in hard rock a 34 meter cavity would be required (OTA report, p. 103). Because of the difficulties in excavating large cavities in hard rock, the analysis of the decoupling scenario generally focuses on salt as the most likely medium. The opportunity to decouple is probably limited to 1 or 2 kt in bedded salt (OTA report, p. 103). For a 5-10 kt threshold regime this would limit the areas of principal concern to those where there are salt domes.

Based on several simplifying assumptions, early theoretical estimates placed the maximum reduction in the amplitude of the p-wave seismic signal from a fully decoupled explosion at approximately 200 at low frequencies (below about 6-10 hertz), reducing to a factor of 7 or so at high frequencies (above about 20 hertz). The decoupling achieved experimentally, in the 0.38 kt "Sterling" test in a salt cavity in Mississippi, was considerably lower, i.e., about a factor of 70 at low frequencies. Seismologists are now in agreement that the experimentally determined decoupling factor of 70 is appropriate at low frequencies (OTA report p. 101). In any case the evader could not count on a decoupling factor larger than that achieved experimentally, particularly since a superpower nuclear testing program of any military significance would involve numerous tests. Moreover, the evader would likely want a further margin of safety. Discounting this added margin but relying on the experimental decoupling factor, the p-wave amplitude of a decoupled 5 kt explosion would be comparable to a 70 ton tamped explosion at low frequencies, and a 700 ton tamped explosion at higher frequencies.

With approximately 10 in-country high performance seismic stations capable of monitoring up to 70 hertz -- for example, the type already installed by NRDC in the Soviet Union -- located within a 1000 kilometers of major salt deposits (close enough to see the high frequencies), the decoupled nuclear explosions above 5 kt could be identified and discriminated from earthquakes. Also, the number of industrial explosions of seismic magnitude equivalent to, or larger than, a fully decoupled 5 kt nuclear explosion that are located in areas favorable for decoupling are relatively few -- on the order of 20 -- and can be monitored by on-site challenge inspections.

As noted previously, NRDC and IRIS, jointly with the Soviet Academy already have established four high performance stations in the Soviet Union; a fifth should be operable by the end of the year; and IRIS is currently negotiating with the Soviet Academy to install 20 high performance stations in the Soviet Union over the next three years. These, and if needed additional stations, could be put in place well before the Soviets could organize a test program based on cavity decoupling.

In addressing the verification requirements above 1-2 kt but below 10 kt the OTA (p. 14) concluded:

> Demonstrating a capability to defeat credible evasion attempts would require seismic stations throughout the Soviet Union (especially in areas of salt deposits), negotiated provisions within the treaty to handle chemical explosions, and stringent testing restrictions to limit decoupling opportunities. If such restrictions could be negotiated, most experts believe that a high quality, well run network of internal stations could monitor a threshold of around 5 kt. Expert opinion about the lowest yields that could reliably be monitored ranges from 1 kt to 10 kt; these differences of opinion stem from differing judgments about what technical provisions can be negotiated into the treaty, how much the use of high frequencies will improve our capability, and what levels of monitoring capability are necessary to give us confidence that the Soviet Union would not risk testing above the threshold.

With regard to yield estimation, at this and lower thresholds it is desirable that the treaty limit the permitted tests to one well calibrated test site, and further, limit the test locations to tightly structured formations below the water table. This would provide for well tamped explosions, thus reducing the dispersion in test yields due to differences in the coupling. With a well calibrated local seismic network, the yields could be measured with an accuracy of about 50 percent (at 95 % confidence) in the 5-10 kt threshold regime. At lower thresholds the uncertainty would increase somewhat, but this is offset by the fact that there is not a need for this level of accuracy.

In sum, there are no technical obstacles to moving to a 5 kt threshold immediately. It should be noted, however, a 5 kt threshold is not very restrictive. According to Ray Kidder, of Lawrence Livermore National Laboratory (LLNL), about 54 percent of the U.S. tests conducted during the five year period, 1980-

1984, were below 15 kt.[4] Assuming the weapons labs can certify a warhead by testing at one-third the design yield, a 5 kt threshold would have prevented only one-half of the approximately 95 nuclear tests conducted during the 1980-1984 period.[5]

1-2 Kiloton Threshold

The threshold for fission boosting with deuterium-tritium (DT) is just under one kiloton. As noted above, the boosted fission primaries of high-yield thermonuclear warheads are between 5 and 20 kt. A 1-2 kt testing threshold, therefore, would prevent the introduction of new warheads with yields greater than 5-10 kt and would severely limit, if not stop, the introduction of new primaries for high-yield thermonuclear weapons. Neutron warheads, some artillery warheads and low-yield atomic demolition munitions (ADMs) could be tested and deployed . Certain weapons effects and reliability tests could be conducted, as could a wide range of physics experiments, including research on all third generation weapons. Eighteen percent of the U.S. weapons tests between 1980 and 1984 were below 5 kt, which means about one-fifth of current testing could go forward under a 1-2 kt threshold assuming testing at one-third the design yield.

As can be seen from Table 2, as the threshold is decreased from 5 to 1 kt the number of industrial explosions and shallow earthquakes in regions suitable for decoupled nuclear explosions increases significantly. The real difficulty is with industrial explosions, the seismic profiles of which presently cannot be distinguished from decoupled nuclear explosions. In order to verify a 1-2 kt threshold we are faced with two alternatives, which are not exclusive. We must develop a comprehensive procedure for monitoring industrial explosions, or rely more extensively on other national technical means, aside from seismology, to detect and identify decoupled nuclear explosions, or do both. In addition, several key scientific issues could benefit from further research.

A comprehensive program for monitoring industrial explosions would probably include the following elements:

- preannouncement of all industrial explosions with yields above the level where they would be confused

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[4] Ray E. Kidder, "Militarily Significant Nuclear Explosive Yields," F.A.S. Public Interest Report, 38, September 1985. This paper was first presented at the DOE sponsored Cavity Decoupling Workshop, Pajaro Dunes, California, July 29-31, 1985 (the workshop paper dated June 25, 1985).

[5] See Thomas B. Cochran, et al., "Unannounced U.S. Nuclear Weapons Tests, 1980-1984," NRDC, NWD 86-1, January 1986, p. 10.

with decoupled nuclear explosions (e.g. above 10 tons for a 2 kt threshold);

- a requirement that all large industrial explosions be ripple, rather than salvo, shots if further research demonstrates that ripple shots have seismic profiles that are distinct from decoupled nuclear explosions;
- a joint program to study Soviet (and U.S.) practices with regard to the detonation of chemical explosions, particularly in areas in which salt domes are known to be present or are likely to be present; and
- on-site monitoring of mining sites in areas suitable for cavities.

Lynn Sykes has also identified three additional areas that would benefit from further study: 1) the discrimination of the seismic waves of small nuclear explosions with seismic magnitudes less than about m_b 3.5 from those of small earthquakes and chemical explosions of comparable magnitude; 2) accurate determination of yield in the 1 to 10 kiloton range; and 3) the effectiveness of high-frequency seismic waves for detection and identification.[6]

In the 1-5 kt range I believe we can dismiss the decoupling evasion scenario on other grounds. First, we should recall that the United States has tested 200-300 times more often than the Soviet Union. While U.S. warheads are believed to have somewhat higher yield-to-weight and yield-to-volume ratios,[7] this does not give the U.S. a significant national security advantage over the Soviets. The Soviets compensate by relying on missiles with greater throwweight. The Soviets, in fact, can throw more megatonnage the same distance. Even if there were extensive testing by the Soviets in the 5-10 kt range in clandestine cavities, at best this could only marginally improve their yield-to-weight and yield-to-volume ratios, but it is not going to give the Soviets a national security advantage.

Second, discussions about cavity decoupling are usually couched in terms of whether a single test can be detected. But today it requires an average of 5-10 tests to develop a new weapon; and this assumes testing under a 150 kt threshold. Third generation weapons will require even more testing. Therefore, the potential evader would have to test tens, or perhaps even hundreds of times in the 5-10 kt regime, to gain some theoretical advantage. In other words, the evader would have to have a robust clandestine

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[6] Lynn R Sykes, "Some Notes on Comprehensive Test Ban Verification," Modern Geology, 1988, 13, pp. 13-20.

[7] See Dan M. Davies and Lynn Sykes, op. cit.

cavity testing program. The evader could not be assured that the cavities could be reused except at yields above 1 kt (OTA report, p. 99). For a 1 kt fully decoupled test in salt the cavity would be 25 meters in radius; 20 meters in hard rock. To prepare a cavity in salt suitable for the full decoupling of a 1 kt test, a 14 kt explosion would be needed (OTA report, p. 98). Alternatively, to create the same cavity by solution mining would take months and require the disposal of large quantities of brine (OTA report, p. 99). The tests would have to be highly instrumented requiring canisters, cables, and equipment of all sorts.

In sum, it is difficult to believe that U.S. intelligence assets, including PHOTINT, SIGINT, and HUMINT, coupled with a challenge on-site inspection program as provided by the treaty, could not deter such a scenario. Since the risks of getting caught would be high and the benefit of testing in the 1-5 kt range small, it is hard to believe such a program would be seriously entertained.

As outlined by Jeremy K. Leggett, "The Role of Confidence-Building Measures in Verification of Low-Yield Threshold and Comprehensive Test Ban Treaties," 1988, several steps could be taken by the U.S. and the Soviets jointly to further reduce the risk of evasion:

- registry of mines, caverns, and salt extraction programs;
- registry of sites of past nuclear explosion sites, particularly PNEs; and
- mapping of areas with high cavity-decoupling risk.

Comprehensive Test Ban

If the risk associated with cavity decoupling tests in the 1-5 kt range can be reduced by reliance on non-seismic national technical means, this will also impact the potential for evasion in to 0-1 kt range. Since the required cavity volume is proportional to yield, as the threshold is reduced cavity excavation becomes proportionally easier and the area suitable for excavation increases. On the other hand the incentive to cheat should lessen as the threshold is lowered. A good case can be made that the nonproliferation benefits of going to zero outweigh the risks associated with possible superpower evasion in the low threshold regime where the probability of detection of evasion is low.

Finally, even under a CTB some activities will be permitted. In this regard several "CTB thresholds" have been proposed:

- Permit testing in dedicated laboratory facilities. Ray Kidder of LLNL, has proposed and made preliminary design studies of a High Energy Density Facility (HEDF), a reusable laboratory chamber that could fully contain explosions up to 300 tons at a rate of one test per week.[8]

- Permit testing in above-ground laboratories with the constraint that workers must be able to be within 10 meters of the explosion center.

- Permit inertial confinement fusion (ICF) experiments, but prohibit any experiments designed to implode fissile material, e.g., highly enriched uranium or plutonium.

- Permit tests with yields less than 100 kilograms TNT equivalent.

A comprehensive treatment of the impact of third generation weapons and physics research of thresholds at these low levels is given by Fenstermacher.[9]

Obviously other variations can be offered. Each of these alternative would require extensive on-site monitoring.

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[8] See Kidder, op. cit.

[9] Dan L. Fenstermacher, "The Effects of Nuclear Test Ban Regimes on Third Generation Weapons Innovation," Harvard University, September 1, 1988 (preprint).

Table 1.

Objectives of Lower Limits on Yields of Nuclear Tests

Threshold	Objective
5-10 kt	Halt the introduction into the stockpile of new high-yield strategic warhead designs and probably the nuclear pumped x-ray laser.
1-2 kt	In addition to the above, halt the introduction into the stockpile of some new tactical warhead designs, new primaries for high yield secondaries and possibly some third generation weapons.
0 kt (CTB)	Depending on the definition of a CTB, in addition to the above, it is possible to halt various physics tests, weapons effects tests and testing of third generation weapons; and the introduction into the stockpile of new low-yield tactical weapons and third generation weapons.

Table 2.
Seismic Events in the USSR/USA Above a Given Threshold

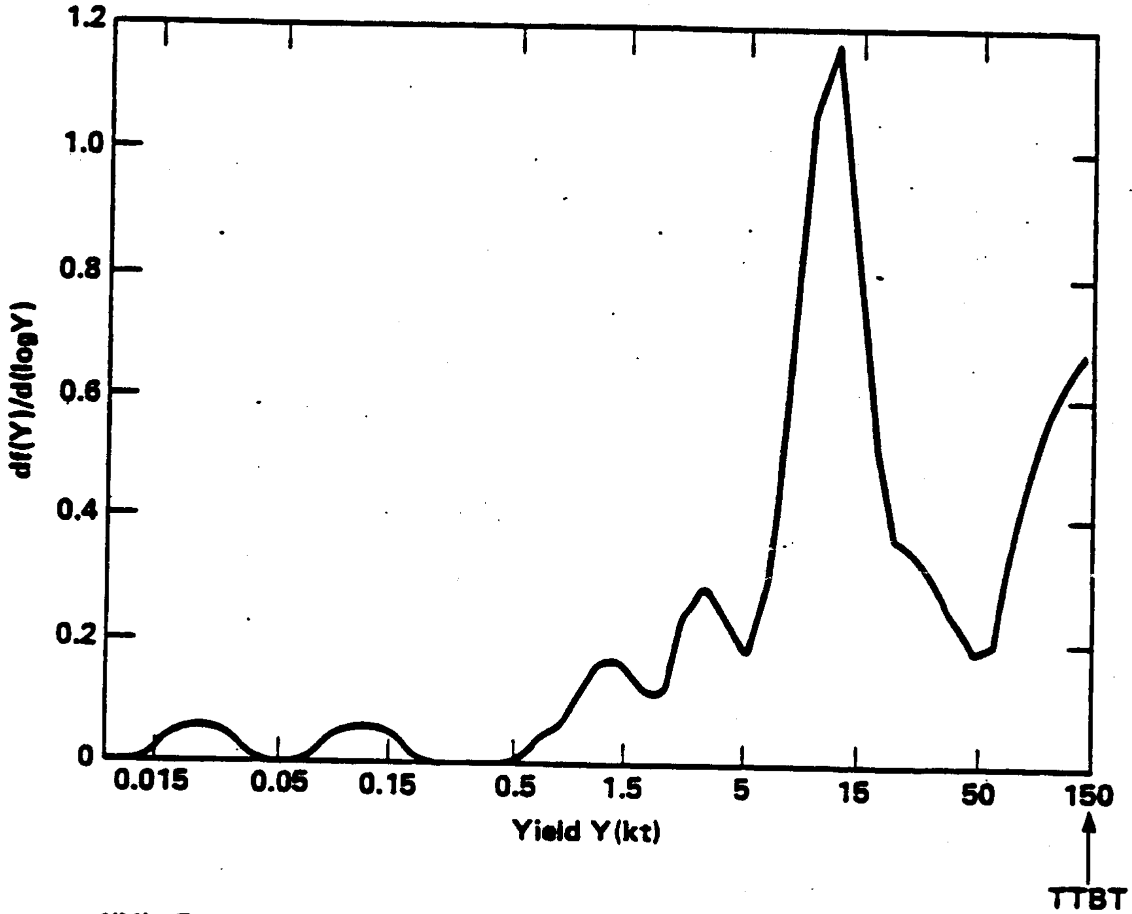
Threshold (kt)	M_b (decoupled nuclear)	Ind. Expl. Yield (tons)	Annual Number of Events: Earthquakes: Continental	Shallow	Industrial Explosions	Industrial plus Shallow Earthquakes	In Decoupling Areas
10	3.25	60	250	50	120	180	4
5	2.95	30	440	90	380	470	25
3	2.75	20	630	120	800	920	74
2	2.55	10	900	180	1700	1800	230
1	2.25	5	1580	320	5000	5300	1300

Source: Charles Archambeau, "The Technical basis for Verification of a Low Threshold or Comprehensive Test Ban Treaty: What is Needed for Verification," 1988.

Figure 1

Distribution of Explosive Yields
at NTS: 1980 through 1984

The curve plotted shows the relative frequency with yield Y versus that yield for all tests at the Nevada Test Site (NTS) from 1980 through 1984. The vertical scale is designed to produce an area under the curve of one so that the relative probability of a test being given yield Y can be seen immediately.



f(Y): Fraction of Tests with Yield Less Than Y
(No Yields Above 150kt)

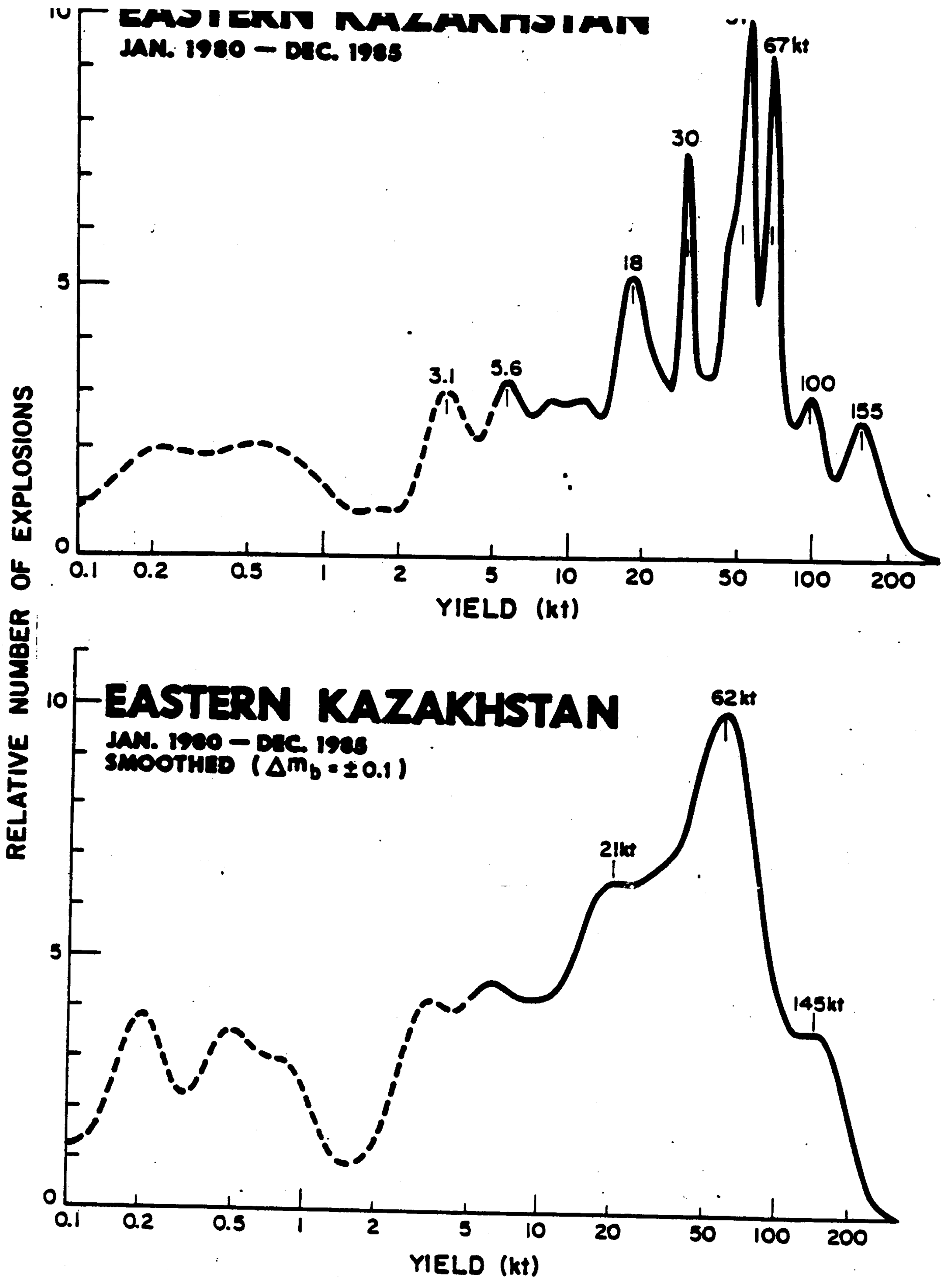

JAN. 1980 — DEC. 1985
67 kt
30
18
3.1
5.6
100
155
0
5
10
0.1
0.2
0.5
1
2
5
10
20
50
100
200
YIELD (kt)
RELATIVE NUMBER OF EXPLOSIONS
EASTERN KAZAKHSTAN
JAN. 1980 — DEC. 1985
SMOOTHED ($\Delta m_b = \pm 0.1$)
62 kt
21 kt
145 kt
0
5
10
0.1
0.2
0.5
1
2
5
10
20
50
100
200
YIELD (kt)

Figure 2.