Chapter 7

Estimating the Yields of Nuclear Explosions

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Chapter 7

Estimating the Yields of Nuclear Explosions

For treaties that limit the testing of nuclear weapons below a specific threshold, the yield of the explosion must also be measured.

INTRODUCTION

Once a seismic event has been detected and identified as a nuclear explosion, the next step is to estimate the yield of the explosion. This is particularly important for monitoring treaties that limit the testing of nuclear weapons below a certain threshold. The process of estimating the yields of Soviet explosions involves three steps: 1) calculate the magnitude of the seismic signal; then, 2) make corrections to adjust for the different geology at each test site; and finally, 3) convert the magnitude into a yield estimate.

The final yield measure describes the explosive energy of a nuclear explosion in terms of kilotons, where 1 kiloton (kt) was originally defined as the explosive power equivalent to 1,000 tons of TNT. This definition was found to be imprecise,[1] however, and so it was agreed in the United States during the Manhattan project that the term "kiloton" would refer to the release of 10^{12} calories of explosive energy.

1 kiloton = 1,000,000,000,000 = 10^{12} calories

While this convention is also followed in the Soviet Union, it does not necessarily mean that the United States and the Soviet Union calculate explosive yields in the same way. Only that part of the total energy released in a nuclear explosion that is immediately available (the so-*called prompt energy release) is* counted in the yield, and there does not appear to be any generally accepted precise definition of what energy release time scale is considered "prompt." Also a complication arises in determining the yield of underground nuclear explosions due to energy released by interaction of the neutrons from the explosive device with the surrounding ground. Consequently, there might be slight differences in how the United States and the Soviet Union measure yields.

Yields can be estimated not only through seismic means, but also by other methods. The other methods are based on analysis of the nuclear byproducts of the explosion (radiochemical methods) or measurements of the speed of the shockwave generated by the explosion in the surrounding rock (hydrodynamic methods). Neither radiochemical nor hydrodynamic methods are currently used by the United States to measure routinely the yields of Soviet explosions because they require access to the test site during the test, and in the case of radiochemical methods, may require information about the weapon design that could reveal sensitive information concerning the characteristics of the weapon.

*The definition is not precise for two reasons. First, there is some variation in the experimental and theoretical values of the explosive energy released by TNT (although the majority of values lie in the range from 900 to 1,100 calories per gram). Second, the term "kiloton" could refer to a short kiloton ($2x10^6$ pounds), a metric kiloton ($2.205x10^6$ pounds), or a long kiloton ($2.24x10^6$ pounds).

MEASURING THE SIZE OF SEISMIC SIGNALS

At present, U.S. estimates of Soviet yields are generally made using seismic waves recorded at teleseismic distances (distances greater than 2,000 km). Seismic magnitudes can be determined from the amplitudes of P waves, Rayleigh waves, and L_g waves.[2] The various magnitudes are averages based on

2A description of the various types of seismic waves is presented in Chapter 3, The Role of Seismology.

recordings at several stations. The magnitudes are then converted to explosive yields using formulas developed through past experience. The formulas used are based on testing experience at the Nevada test site and at the test site operated in the Sahara by France in the 1960s. The three magnitude measures most often used in yield estimation are: the P-wave magnitude m_b the surface wave magnitude Ms, and the L_g-wave magnitude $m_b(L_g)$.

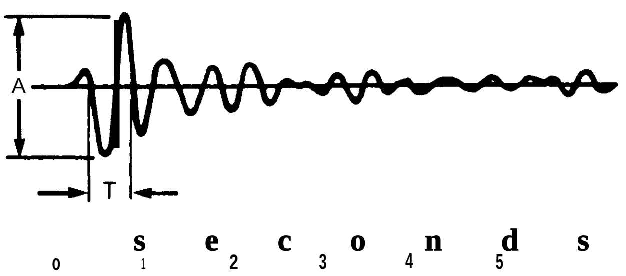
The m_b is computed from measurements of P-wave recordings by the use of the formula

$$m_b = \log (A/T) + B.$$

As illustrated in figure 7-1, A is the largest P-wave amplitude in nanometers (0.000000001 meters) measured peak-to-peak from a seismic short-period recording during the first few seconds of the P wave and correcting it for the instrument magnification, T is the duration of one cycle of the wave in seconds near the point on the record where the amplitude was measured (for P waves the period is typically 0.5 to 1.5 seconds), and B is a distance-dependent correction term that compensates for the change of P-wave amplitudes with distance.

The surface wave magnitude is determined by measuring the Rayleigh-wave amplitude near the point where the dominant period of the wave is nearest to 20 seconds on long-period vertical component records. The formula used is

Figure 7-1.–Computation of P-Wave Magnitude



Measurement made on P waves to obtain the magnitude of a seismic event. The peak-to-peak amplitude (A) in the first few seconds of the P wave is corrected for the instrument magnification at the dominant period T.

$$M_s = \log (A/T) + D,$$

where A and T are the amplitude and the period measured off long-period vertical component seismic recordings, again in nanometers and seconds, and D is a distance-dependent correction term for Rayleigh waves.

The magnitude measure derived from measurements of L_g waves is computed from the formula

$$m_b(L_g) = 5.0 + \log [A(10km)/110],$$

where A(10 km) is the maximum sustained amplitude of L_g on short-period vertical records in nanometers extrapolated backwards to a distance 10 km from the source by dividing by the geometrical spreading factor of $d^{-5/6}$, where d is the source-to-receiver distance, and by the estimated attenuation along the path. The empirical $m_b(L_g)$ v. log Yield (Y) relationship also includes a small second-order term, giving

$$m_b(L_g) = 3.943 + 1.124 \log Y -0.0829 (\log Y)^2$$

for explosions in water saturated rocks such as those at the Nevada Test Site.

The m_b magnitude is routinely used at teleseismic distances for yield estimation because P waves are detectable at large distances, even for small seismic events. This measure can almost always be obtained for any seismic event that is detected. The measurement of M_s requires a larger event, because Rayleigh waves are small for nuclear explosions. For explosions below 50 kt, M_s may be missed altogether at teleseismic distances. The L_g amplitude is similarly weak for small explosions. Consequently, it maybe important for seismic stations to be close to the explosion if surface waves and L_g waves are to be used for yield estimation of explosions less than 50 kt. This is one of the reasons why seismic stations within the territories of the treaty participants are desirable. The distance correction factors can be quite variable regionally, and hence, some of the magnitude-yield relationships will need to be adjusted for different regions.

In addition to the conventional surface wave magnitude M_s, a new measure of source strength for surface waves is coming into wide use. Called *seismic moment* (MO), it is an estimate of the strength of a compressional (explosion-like) force at the explosion site. Seismic moment gives a direct description of the force system, acting in the Earth, that would make seismic waves of the size and shape actually recorded. The advantage of using seismic moment is that the computation can correct for the estimated effects of contamination of the seismic signals due to earthquake-like motion triggered by the explosion. This is useful because nuclear explosions often release stress that has been built up in the area of the explosion by geological processes. The release of built-up stress by the explosion creates a surface wave pattern similar to that observed for earthquakes, which is seen superimposed on the signals of the explosion. Characteristics of an earthquake, such as Love waves and reversed polarities in the Rayleigh waves, are often observed from a nuclear explosion, indicating release of pm-existing stress. If not removed, this release of natural stress by the explosion, called *tectonic release, can* distort yield estimates obtained from conventional M_s.

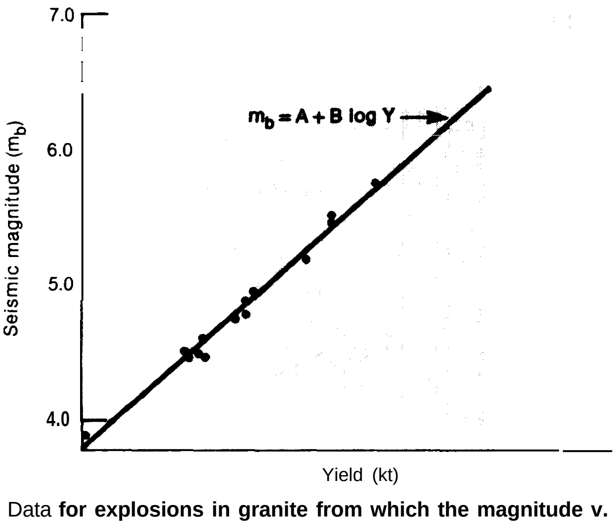
DETERMINING EXPLOSIVE YIELD FROM SEISMIC MAGNITUDE

Once the seismic magnitude measurements have been made, the next step is to relate the magnitude measurements to the yield of the explosion. Because we know the actual yields only of U.S. tests and some French nuclear explosions (the Soviets have announced yields only for a few of their tests), our knowledge is based on data other than Soviet data. The actual data used to derive this relationship are shown in figure 7-2. The relationship between the yield of a nuclear explosion and the measured seismic magnitude can be described using an equation of the general form

$$M = A + B \log Y + \text{Bias Correction}$$

where M is a magnitude measure (or moment) from surface waves, body waves, or L_g waves, A and B are constants that depend on which magnitude measure is used, and Y is the yield in kilotons. The specific constants used by the United States for these calculations are classified. The "Bias Correction" term is an adjustment made to correct for the differences in how efficiently seismic waves travel from the various test sites. This correction is particularly important for m_b, because short-period body waves are strongly affected by the physical state (especially temperature) of the medium through which they travel.

Figure 7-2.—Explosions in Granite



Data **for explosions in granite from which the magnitude v. yield equation is derived.**

SOURCE: Modified *from Air* Force Technical Application *Center.*

The empirical magnitude-yield relationships for m_b that are used to estimate yields at inaccessible test sites in the U.S.S.R. and elsewhere have been revised several times during the last two decades. These revisions were improvements in yield formulas and computational procedures to correct for such problems as difficulties in merging magnitude sets from different station configurations and instruments, clipping (limiting the maximum recordable amplitudes) of large signals by the recording systems, and not correctly accounting for differences in the geology at different test sites. The early magnitude-yield formulas were based on the simplifying assumption that all nuclear explosions in granite at any site follow a simple linear relationship between m_b and log(yield). After the factors listed above were properly considered, however, it became obvious that bias corrections for each test site were needed.

SOURCES OF UNCERTAINTY

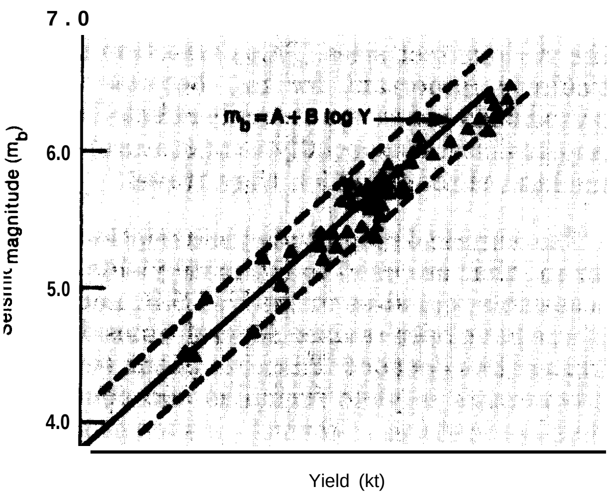
Under the ideal conditions of a perfectly uniform and symmetrical Earth, it would be possible to estimate yields of nuclear explosions at any site from measurements at a single seismic station. In practice, however, seismic magnitudes and magnitude-yield plots show scatter. Using data from the International Seismological Centre[3] as an example, individual m_b measurements typically have a standard deviation of 0.3 to 0.4 magnitude units before station corrections are applied. When station corrections are applied, the standard deviation is reduced to 0.1 to 0.15 units. Figure 7-3 illustrates typical scatter in a magnitude-yield plot.

[3] The International Seismological Centre is an organization based in England that gathers data for the research community from thousands of seismic stations operated all over the globe.

One reason for this variation is the small-scale geologic contrasts in the Earth that cause focusing and scattering of seismic waves. Focusing effects near the recording seismometers can create differences in estimated magnitudes even when the stations are closely spaced. Focusing effects near the explosion can cause broad regional variations of seismic amplitudes so that seismic observatories over whole continents may observe higher or lower average amplitudes than the global average. Fortunately, the uncertainty introduced by focusing effects can be reduced by averaging measurements from numerous stations if the stations are well distributed around the test sites in both distance and direction.

In addition to the scatter due to focusing, geological structures under individual stations may amplify seismic waves. Such effects may

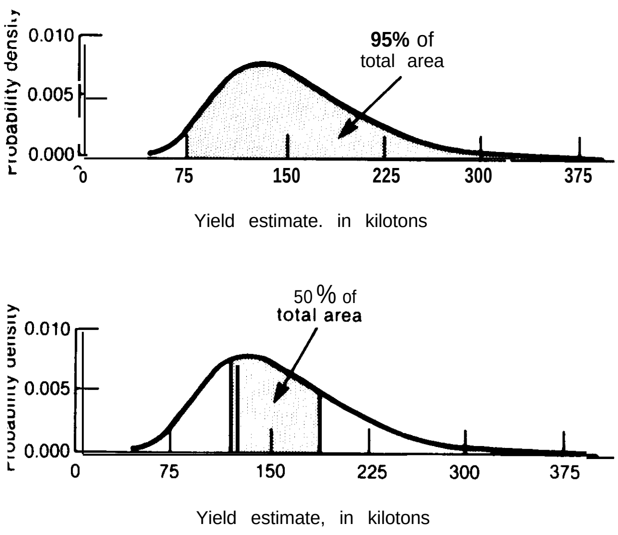
Figure 7-3.—Yield Data From the Nevada Test Site



M_b versus yield for explosions at the Nevada Test Site. The scatter is characteristic of yield measurements when only P-wave magnitudes are used.

SOURCE: Modified from Air Force Technical Applications Center.

Figure 7-4.—Yield Estimate Distribution



Probability of yield estimates for a 150 kt explosion measured with a factor-of-2 uncertainty.

be corrected for by applying statistically derived station corrections that compensate for any such local effects.

After averaging many measurements and applying appropriate corrections, estimates of the yield of a nuclear explosion are expected to be distributed about the "true" value in the manner indicated in figure 7-4. The horizontal axis in this figure is the yield estimate while the vertical axis is the probability that the estimate is correct. The area under the curve between 2 yield values represents the probability that the actual yield is in this interval (the percentage chance is 100 times the probability and the total area under the curve is 1, giving a 100 percent chance that some value of magnitude will be measured). This figure shows that it is most likely that the central yield value (150 kt in this case) will be close to the actual value and that outcomes become increasingly less likely the larger the difference between the estimated *value* and the central value (see chapter 2 for a more detailed discussion of uncertainty and what it represents). The yield distribution is asymmetric due to the normal distribution of m_b and the logarithmic relationship between the yield of the explosion and the measured seismic magnitude. Figure 7-3 is a typical empirical magnitude-yield curve obtained from actual data at the Nevada test site that shows the measurements do not follow a single line but scatter around it because of measurement errors and variations in rocks surrounding the explosions.

Some of the uncertainty described above is due to variations in how well explosions are coupled to the surrounding rock. Also, explosion depth can influence the amplitudes of the seismic waves emitted, as can variations in the physical properties of the Earth. For inaccessible test sites, these effects result in increased uncertainty in estimating yields. However, if data were exchanged and calibration shots performed, corrections could be made that would greatly reduce the uncertainty. Nevertheless, there will always be some uncertainty in estimates of the yields of Soviet explosions, as in estimates of any physical quantity. This is not unique to seismology. Some uncertainty will exist no matter what type of measurement system is used. Such uncertainty should not necessarily be considered to represent opportunities for cheating. Chapter 2 discusses the meaning of the various uncertainties and their implications for cheating.

BIAS CORRECTION FOR SOVIET NUCLEAR EXPLOSIONS

In estimating the yields of Soviet explosions, a major concern is how well the magnitude-yield formula for U.S. tests can be applied to Soviet test sites. Geophysical research has shown that *seismic* P waves traveling through the Earth's mantle under the main U.S. test site in Nevada (and many other areas of the world as well) are severely attenuated when compared to most other continental areas, especially those with no history of recent plate tectonic movements. If not corrected for, this attenuation will cause a sizable systematic error in estimates of the yield of Soviet explosions.

The apparent reason for this attenuation is the high temperature in the upper mantle under Nevada and many other tectonically active regions. Regions of high temperatures change the elastic and absorptive properties of the rocks, causing a large loss in the amplitudes of seismic waves traveling through them. Similar phenomena are thought to occur under the French test sites in Algeria and the Pacific, though not under either the Soviet test sites in Kazakh and Novaya Zemlya or the U.S. test sites in Mississippi and Amchitka. If the P-wave magnitudes observed from U.S. tests in Nevada are used as a basis for estimating yields, most Soviet explosions which have been exploded in areas where the upper mantle is cool and there is little attenuation of P waves will appear considerably larger than they actually are.

The evidence for such attenuation effects comes from many studies, including:

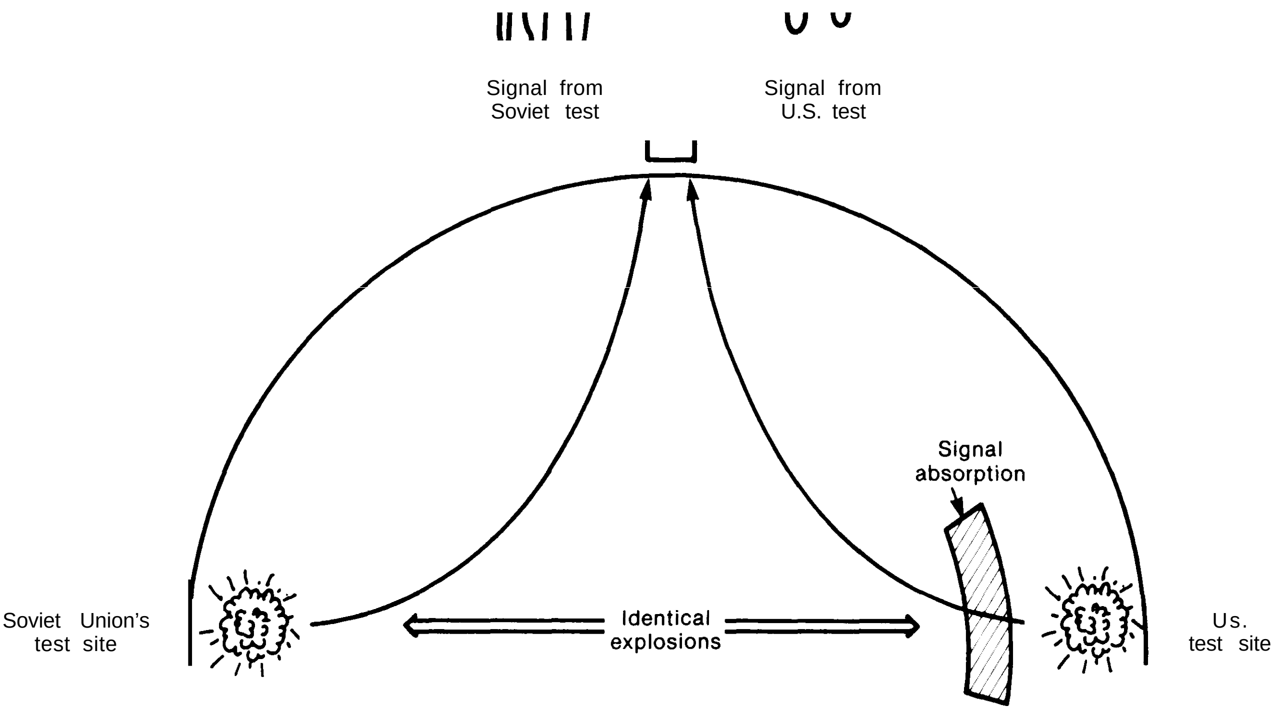
- comparisons of P-wave amplitudes observed at the Nevada test site with observations made at other sites in areas underlain by colder mantle;
- studies of short period S-wave amplitudes, which are very sensitive measures of mantle temperature variations;
- studies of the frequency content of both P and S waves, i.e., the relative loss of high frequency energy in waves traveling through the upper mantle in both directions under Nevada; and
- studies of P- and S-wave velocities, which are also influenced by temperature.

In addition, there is a large amount of independent geophysical evidence supporting the notion of anomalously high temperatures under most of the western United States. This evidence includes:

- measurements of anomalously high heat flow,
- measurements of electrical conductivity, and
- the low velocity P waves (P_n) and the absence of S waves (S_n) that propagate just under the Earth's crust.

These "symptoms" of high attenuation have been observed in many other areas of the world and are recognized as such by most geophysicists. The sketch in figure 7-5 illustrates how

Figure 7-5.—Schematic Illustration of Attenuation. Related Magnitude Bias



Seismic body waves crossing parts of the upper mantle with high temperatures become anonymously reduced in amplitude. Seismic signals from the Soviet Union's test site appear much larger than signals from an identical explosion conducted at the U.S. test site.

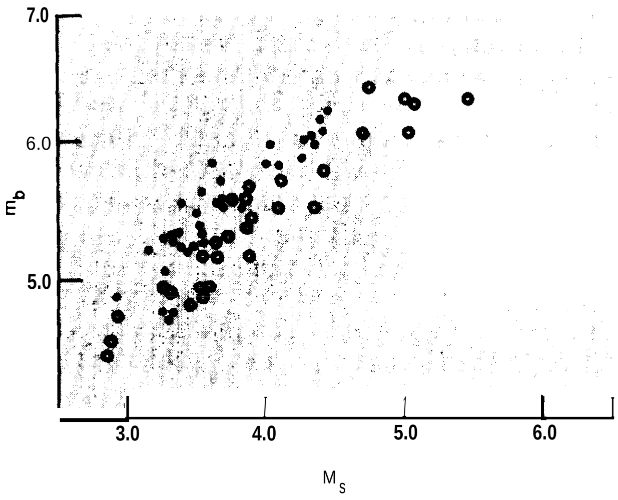
SOURCE: Modified from Defense Advanced Research Projects Agency.

this attenuation is created in the Earth and affects estimates of the size of the wave source. Seismic body waves crossing the hatched high attenuation zones in the upper mantle are reduced in amplitude and high frequency components of wave motion relative to waves that bypass such zones.

Magnitudes derived from Rayleigh waves and L_g waves are less influenced by temperature variations in the mantle because they travel along the surface and largely bypass the high attenuation zones in the upper mantle. A plot of P-wave magnitudes (rob) against surface wave magnitudes (M_s) should, therefore, show the attenuation of P waves relative to surface waves. By plotting the M_s - m_b ratio of explosions for different test areas, the attenuation indifferent regions can be compared. Figure 7-6 shows the results of an early study that compared the M_s - m_b for explosions in Eurasia with the M_s - m_b for explosions in North America. It can be seen that the two groups are offset, with explosions of the same M_s value having lower m_b values in North America than in Eurasia. Results like this led to early speculation about the existence of high attenuation zones in the upper mantle.

In general, if the P-wave magnitudes are plotted against the Rayleigh or L_g magnitudes for the Nevada and Soviet test sites, the 2 sets of data are offset by about 0.3 to 0.4 magnitude units (or an amplitude factor of about 2 for P waves).[4] The most likely explanation for this offset is the reduction of P-wave magnitudes due to attenuation at the Nevada test site. Such data constitute additional support for the idea of an attenuation bias for P waves. Offsets can also be brought about by other factors such as contamination of the M_s measurement by tectonic release. However, such contamination can be detected by the strong Love waves the release generates, and

Figure 7-6.—Comparisons of Explosions in Eurasia With Explosions in North America



Explosions

• Eurasia o North America

Explosions with the same M_s value have lower m_b values in North American than in Eurasia. This led to early speculation about the existence of high attenuation zones in the upper mantle.

SOURCE: Modified from P.D. Marshall and P.W. Basham, *Geophysical Journal of the Royal Astronomical Society, 1972, vol. 28,* pp. 431-458.

reduced by using seismic moment instead of surface wave magnitude (M_s) for yield estimation.

Various government-supported scientific panels of seismologists, after considering the totality of the geophysical evidence, have repeatedly recommended during the last decade that U.S. yield estimates of Soviet explosions be reduced by subtracting a larger “Bias Correction” term from the magnitudes to account for the attenuation effect on m_b. As a result, the bias correction has been increased on several occasions over the last decade as new scientific evidence indicated that such changes are appropriate.

The size of the bias correction was determined simply by averaging the correction inferred from a number of independent *or semi*-independent estimates of the attenuation effect made by different researchers. Most evidence for an attenuation “bias” has been indirect thus far, although the evidence from

[4] See for example P. D. Marshall and P. W. Basham, “Discrimination Between Earthquakes and Underground Explosions Employing an Improved M_s Scale,” ***Geophysical Journal*** *of the* ***Royal Astronomical Society***, vol. 28, pp. 431-458, 1972, and Otto W. Nuttli, “L_g Magnitudes of Selected East Kazakhstan Underground Explosions,” ***Bulletin*** *of the Seismological Society of* ***America***, vol. 76, No, 5, pp. 1241-1252, October 1986.

global seismic studies and seismological experience gives strong support to the idea. More direct measurements of this bias may soon become available. The United States and Soviet Union have recently agreed on experiments to calibrate seismic yield estimation methods through measurements at each others test sites. Explosions will be measured with seismic methods and the yields confirmed independently by hydrodynamic methods. In addition, several seismic stations have been set up recently in the Soviet Union near the Kazakh test site by a group of U.S. scientists supported through the Natural Resources Defense Council. Data from these stations will help improve estimates of the bias correction and assess the efficiency of seismic wave propagation at high frequencies to regional distances.

The bias correction is currently used as a simple, yield-independent adjustment to the intercept, A, in the rob-log Y curve. The value currently used by the U.S. Government is intended to be the most appropriate value for yields near the 150 kt threshold of the 1974 Threshold Test Ban Treaty. A different bias may be appropriate for yields that are either much larger or much smaller.

REDUCING UNCERTAINTIES

The estimated yield of an underground of nuclear explosion, like any quantity derived from measurements, has some error associated with it. The error comes from a variety of sources. Some of the error is considered to be *random* in that it varies unpredictably from one measurement to another. Other errors are not random but are *systematic*. Systematic errors are those that always act in the same way, for example, the bias between test sites. If systematic errors are understood, corrections can be made to reduce or eliminate the error.

The distinction between random and systematic errors, however, has no clear boundary. If everything about the Earth and seismic waves were known, almost all errors in seismology would be systematic. In general, random errors usually turn out to be systematic errors once the reason for the error is understood. However, if the systematic errors are not understood, or if there are lots of systematic errors all operating indifferent ways, then the systematic errors are often approximated as random error. In such cases, random uncertainties are inflated to encompass the unexplained systematic uncertainties.[5]

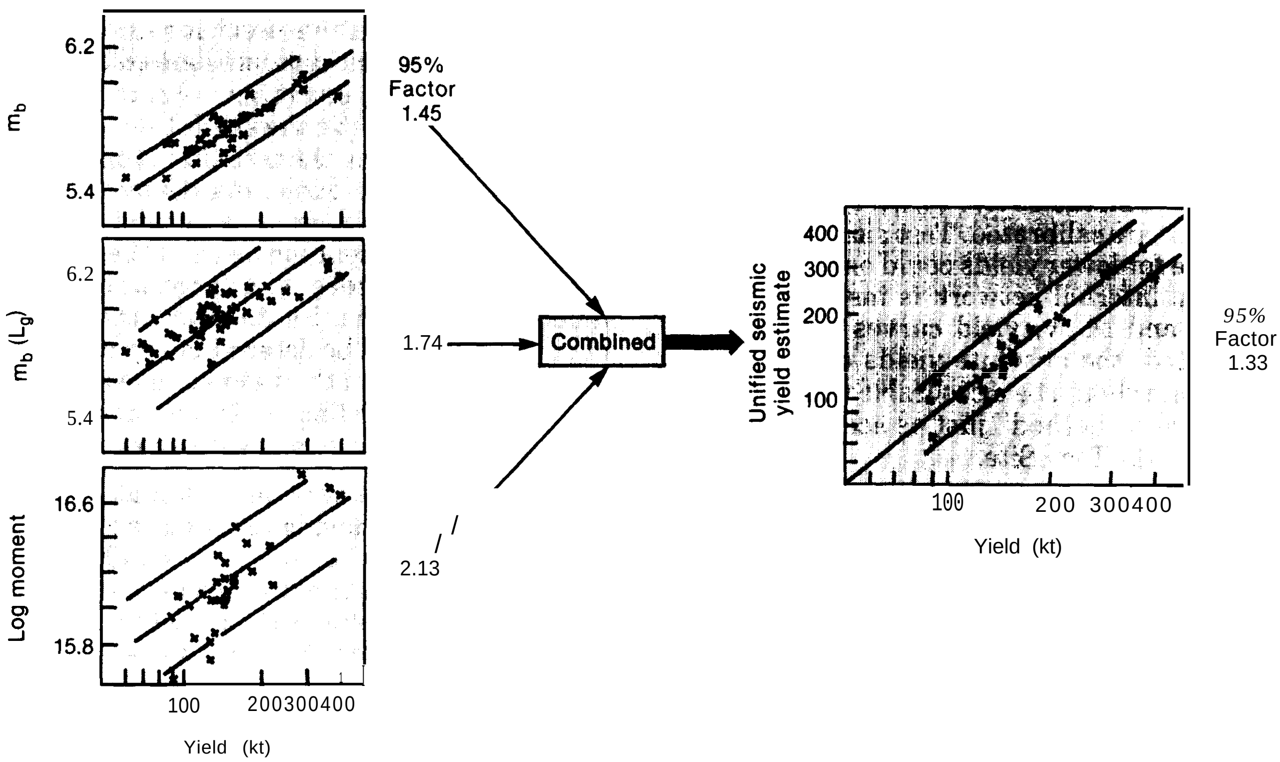
Random Uncertainty

Different methods of yield estimation have different accuracies and uncertainties. At the Nevada test site, the most precise method uses P-wave magnitudes (rob). Less precise methods use L_g waves ($m_b(L_g)$), surface waves (M_s), and seismic moment (M_o) At the Nevada test site, yields estimated from m_b alone have a random uncertainty factor of 1.45 at the 95 percent confidence level, whereas those from $m_b(L_g)$ have an uncertainty factor of 1.74, and those from M_o have an uncertainty factor of 2.13.

Recently, the Defense Advanced Research Projects Agency (DARPA) has been able to reduce the random uncertainty in seismic yield estimates at the Nevada test site by combining measurements made by the three different methods. Scientists have shown, using data from U.S. explosions at the Nevada test site, that the random errors of the three types of magnitude measures for a given event can be considered statistically independent. Consequently, an improvement in the accuracy of yield estimates can be achieved by combining several methods to produce a “unified” magnitude measure. By forming a weighted average of the three magnitudes, a “unified seismic magnitude” with an uncertainty factor of 1.33 (figure 7-7) has been derived. Most seismologists believe that if this method were now

‘As discussed in Chapter 2, random errors do not provide opportunities for cheating. However, if systematic errors are found to be 1) of sufficient size, 2) usable for an advantage by one side, and 3) unrecognized as being systematic by the other side, then such errors can be exploited under some situations. A treaty should, therefore, contain provisions to reduce the uncertainty of yield estimates and counter evasion opportunities.

Figure 7-7.—Uncertainty in Yield Estimates



Uncertainty in yield estimates can be greatly reduced through the use of a unified seismic yield estimate. On the left are three plots of m_b, $m_b(L_g)$, and M_o versus yield at the Nevada Test Site. On the right is a similar plot of the unified seismic yield estimate versus the actual yields. The 95 percent uncertainty factors are shown to the right of each plot.

SOURCE: Modified from Defense Advanced Research Projects Agency.

applied to estimating yields at the Soviet test site in Eastern Kazakh, the uncertainty would be reduced to a factor of 1.6- 1.5 for explosions around 150 kilotons.[6] What limits the uncertainty from being reduced to the level of the Nevada test site (a factor of 1.3) is the systematic uncertainty or bias correction. As we will see later, however, this systematic uncertainty can be reduced through calibration shots.

The expected precision given above are only for explosions where all waves are used for the estimation. For smaller explosions, the regional Rayleigh and L waves are not always strong enough to travel the long distances required to reach seismic stations outside the Soviet Union. Consequently, for monitoring low-yield explosions, stations within the Soviet Union may be necessary to obtain the improved accuracy of the "unified seismic yield" estimation method. The relationship between magnitude and yield for the stations within the Soviet Union will also have to be established.

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[6] Consider, as an example, the situation where there are 3 statistically independent methods of calculating the yield of an explosion, all of which (for the sake of this example) have a factor of 2 uncertainty in a log normal distribution:

# of Methods	Resulting Uncertainty
1	2.0
2	1.6
3	1.5

By combining methods, the resulting uncertainty can be reduced. This methodology, however, can only reduce the random uncertainty. Systematic uncertainty such as differences between the test sites will remain and limit the extent to which the uncertainty can be reduced unless calibration is performed.

As noted above, the formulas derived from the Nevada test site data that describe the relationships between yield and $m_b(L_g)$ and moment M_0 are not directly applicable to the Soviet test site in Kazakh without some as yet unknown adjustments. The values of these adjustments can be determined if stations are placed within the Soviet Union and the Soviet test sites are calibrated. Test site calibrations suitable for lower yields could only take place after an internal network is installed. If the $m_b(L_g)$ and M_0 v. yield curves are suitably calibrated, the absolute yields of explosions at Kazakh should be measurable with the "unified seismic method" just as accurately as at the Nevada Test Site.

The above analysis applies only to explosions at known test sites observed by a large set of well-distributed seismic stations for which the appropriate station corrections and bias correction have been determined. The accuracy with which the yields of "off-site" nuclear tests could be estimated would be less than that stated above. Therefore, to maintain high accuracy in yield estimation, nuclear testing should be prohibited outside specified, calibrated test sites.

Most yield estimation research has concentrated on yields around 150 kt, so the accuracy that could be achieved by seismic methods at lower yields is not yet well known. In any future low threshold test ban treaty, it might be expected that the initial uncertainties in yield estimation for explosions below 10 kt would be large. These uncertainties would then be reduced as more data were gathered, as our knowledge of wave propagation properties for various paths in the monitored regions was refined, and as calibration information was obtained.

Systematic Uncertainty

The yield estimation precision described above for teleseismic data are limited because of systematic uncertainties. As discussed above, the systematic uncertainty can be reduced by calibrating the test site. Calibrating a test site involves exploding devices whose yields are either known or accurately determined by independent means, and then measuring the magnitudes at a large number of monitoring stations. By doing so, the yields of other events can be determined by comparing the amplitudes of the seismic waves at common seismic recording stations with those originating from the events with known yields.

This approach reduces the systematic uncertainties caused by having to estimate the varying properties of the rocks surrounding the explosion and any focusing effects near the explosion sites. As long as these factors remain approximately unchanged within a geologically uniform area, the calibration improves the estimation of yields.

The sizes and numbers of geophysically distinct subdivisions in any test site depend on the geological structures of the area. A specific calibration maybe valid only for a limited area around the shot if, at larger distances, the rock properties and focusing effects change. The distances over which the relevant conditions change vary, depending on the local geology. Testing areas that are large or contain varying geology would obviously need more calibration shots than areas that are geologically uniform. If calibration were performed at the Soviet test site, the expected seismic yield estimation capability would be comparable to the existing seismic capability at the Nevada Test Site.

YIELD ESTIMATION CAPABILITIES

In considering the capability of all methods of yield estimation, it must be kept in mind that it is never possible to determine a yield without some uncertainty. The standard against which yield estimation methods are measured is radiochemical methods. Radiochemical methods of yield estimation have an uncertainty of about 10 percent (a factor of 1.1). Also, experimental devices often detonate with yields that are slightly different from what was predicted.

This uncertainty in predicted yield was recognized during the negotiations of the Threshold Test Ban Treaty and provisions were established for unintended breaches (see ch. 2).

The yields of Soviet underground explosions can be seismically estimated with a much better capability than the factor-of-2 uncertainty that is commonly reported.[7] New seismic methods have greatly improved yield estimation capabilities. Further improvements would occur if the test sites were calibrated and, for small tests, if stations were present within the Soviet Union during the calibration. The capabilities depending on these variables can be summarized as follows:

- *Without Calibration:* For large explosions (above 50 kilotons) seismic yield estimation could be improved with the additional use of the other methods including: surface waves, L_g waves, and seismic moment. Through such a combined method, it is estimated that without calibration Soviet yields can be seismically measured with present resources to a factor of 1.6 to 1.5 uncertainty.
- *With Calibration:* Further reductions in the uncertainty of yield estimates can be accomplished if the Soviet test site were calibrated. At a defined, well-calibrated Soviet test site, it is estimated that yields could be seismically measured with the same factor of 1.3 uncertainty that is found for seismic estimates at the Nevada Test Site. In fact, Soviet seismologists have told U.S. seismologists that they are able to estimate yields seismically at their own test site with only a factor of 1.2 uncertainty.
- Small *Explosions:* For small explosions (below 50-kt), the regional seismic waves may not always be strong enough to travel long distances to seismic stations outside the Soviet Union. Consequently, seismic stations within the Soviet Union may be necessary (in addition to calibration) to obtain the 1.3 factor of uncertainty from combined seismic methods for explosion with yields below 50 kt. At yields below 10 kt small variations of the physical environment may produce greater uncertainty. Therefore, at yields below 10 kt, the uncertainty may be inherently greater.

A 1.3 factor of uncertainty (for yields above 50 kt) is the claimed capability of the hydrodynamic yield estimation method using CORRTEX data[8] that has been proposed as an alternative means for improving yield estimation. Consequently, hydrodynamic yield estimation will not provide a significantly superior yield estimation capability over what could be obtained through well-calibrated seismic means (also a 1.3 factor of uncertainty). Hydrodynamic yield estimation is, however, one of the methods that could be used to provide independent estimates of the yields of calibration shots to improve seismic methods. Once a test site was calibrated using hydrodynamic methods, there would be no need to continue the use of those intrusive methods.

[7]See, for example, ***Verifying Nuclear Testing Limitations:*** *Possible U.S.-Soviet Cooperation* (Washington, DC: U.S. Department of State, Bureau of Public Affairs, Special Report No. 152, Aug. 14, 1986)

[8]See appendix, *Hydrodynamic Methods of* ***Yield*** *Estimation.*

SOVIET TEST PRACTICES AND TEST BAN COMPLIANCE

Specific concern over compliance with test ban treaties has been heightened with findings by the Reagan Administration that:

> Soviet nuclear testing activities for a number of tests constitute a likely violation of the legal obligations under the Threshold Test Ban Treaty.[9]

Such findings are presumably based on net assessments of all sources of data. In measuring yields near the 150 kt limit of the Threshold Test Ban Treaty, however, seismic evidence is considered the most reliable basis for estimating the yields of Soviet underground nuclear explosions.[10] It is, therefore, the seismic evidence that has received particular attention.

Concern about whether the Soviet Union is actually restricting its testing to a maximum yield of 150 kt is motivated by two arguments:

1. The m_b of several Soviet tests at their Shagan River (E. Kazakhstan) test site are significantly larger than the m_b for U.S. tests with yields of 150 kt.
2. The pattern of Soviet testing indicates that the yields of Soviet tests increased after the first 2 years of the treaty.

The validity of the first argument is dependent on how the Soviet yields are calculated. Because of the uncertainty in measuring the yields of Soviet tests using only m_b and because of differences in opinion as to what the correct bias value for Soviet tests should be, there is disagreement as to whether the m_b values of the largest Soviet tests do, in fact, represent violations of the 150 kt limit of the Threshold Test Ban Treaty. For example, when calculations such as those in table 7-1 are made using both m_b and M_S measurements and a bias correction of 0.35, they indicate that the few remaining yields estimated as above 150 kt are well within the expected random scatter, and do not support claims of a violation.

The second argument is dependent on assumptions about probable Soviet behavior. Two years after the signing of the Threshold

[9]"The President's Unclassified Report on Soviet Noncompliance with Arms Control Agreements, " transmitted to the Congress Mar. 10, 1987.

[10]Conclusion of the Defense Intelligence Agency Review Panel as stated in a letter from Roger E. Batzel, Director of Lawrence Livermore National Laboratory to Senator Claiborne Pen on Feb. 13, 1987.

Box 7-A.—Calculations of the Six Largest East Kazakhstan Explosions. By Sykes et al., Based on Unclassified Data

6 Largest East Kazakhstan Explosions 1976-1986

Date	Yield from m_b only	Yield averaged from m_b & M_S
23 June 79	152	149
14 Sept 80	150	150*
27 Dec 81	176	161
4 July 82	158	158*
14 July 84	140	140*
27 Oct 84	140	140*
	Average: 152.7 (± 13.4 kt)	Average: 149.7 (± 8.8 kt)

(*based on m_b only; no M_s determined)

All estimated yields are well within the uncertainty expected for observance of the150 kt threshold limit.

SOURCE: Calculations of the six largest East Kazakhstan explosions made by Sykes et al., based on unclassified data. Body wave measurements from International Seismological Centre Bulletins and United States Geological Survey Reports. Station corrections determined to be 0.02 to 0.04 from mean. Surface wave calculations made by Sykes et al. Calibration corrected for bias using a value of 0.35 to make body wave data consistent with surface wave data.

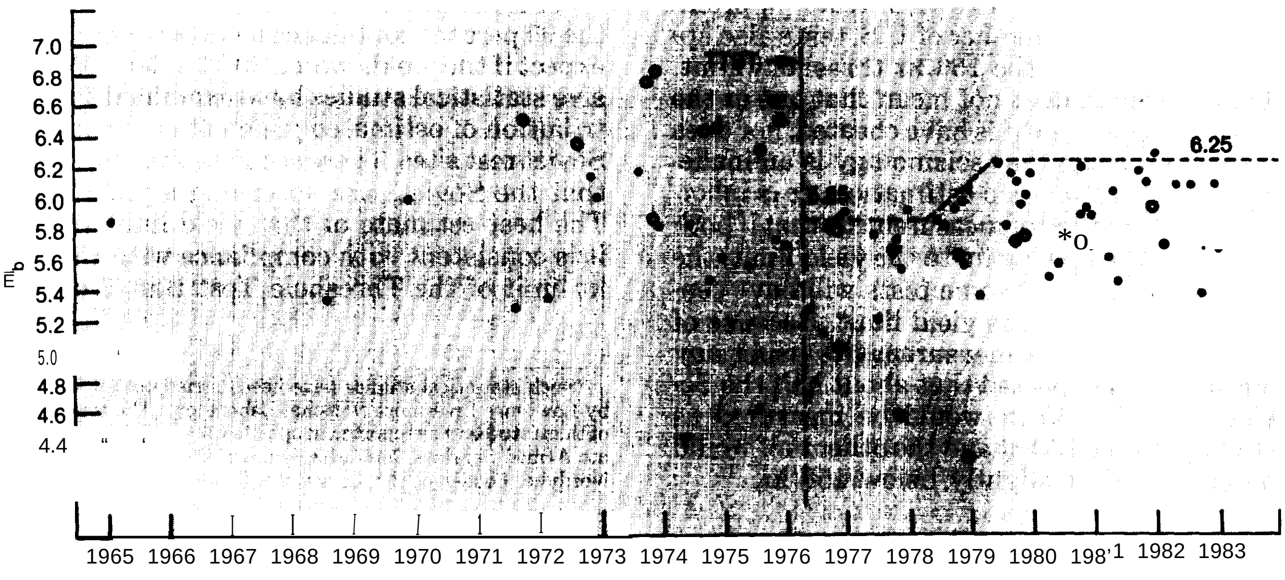
Test Ban Treaty, the size of the largest Soviet explosions at their eastern Kazakh test site increased markedly (see figure 7-8).[11] This increase has been interpreted by some to infer that the Soviets have been violating the 150 kt threshold limit in the later tests. The argument assumes that the Soviets were testing up to the limit for the first 2 years and, therefore, by inference, have been testing above the limit in violation of the treaty ever since 1978. Alternate interpretations for this apparent yield increase have been offered. It has been pointed out that a similar pattern of testing occurred at Kazakh for the 2 years prior to the treaty. It has also been speculated that this increase in yields may reflect a Soviet decision to move their high yield testing from the Novaya Zemlya test site to the Kazah test site.[12] As anon-technical consideration, it can be argued that if the Soviets had tested above the limit of the Threshold Test Ban Treaty at the Kazakh test site, they would never have offered to allow the United States to calibrate their test site using CORRTEX and Soviet test explosions. The calibration will reduce the uncertainty of yield estimates, a reduction that applies to past as well as future explosions and hence can provide more accurate evidence concerning past compliance.

Because of the statistical nature of all yield estimates, the question of compliance can be addressed best not by looking at individual tests but rather by examining the entire pattern of Soviet testing. It is particularly useful to compare the testing programs of the United States and the Soviet Union. It can be seen from figure 7-9 that if a bias value lower than 0.35 is used, there appears to have been about 10 (out of over 200) Soviet tests since the signing of the Threshold Test Ban Treaty in 1974 with yield central values above the 150 kt threshold limit. When the same method of yield

[11] **There was** also **speculation** that this increase **was** coincident with a change in the U.S. official method of yield estimation. For example, Jack Anderson, "Can't Tell If Russia Cheats On Test Ban," *The **Washington** Post,* Aug. 10, 1982, p. C15.

[12] **See** for example, "Nuclear Test Yields" (Letter to the Editor), J. F. **Evernden** and L. R. Sykes, *Science,* vol. 223, Feb. 17, 1984, p. 642.

Figure 7-8.—m_b Versus Time for Large Soviet Explosions

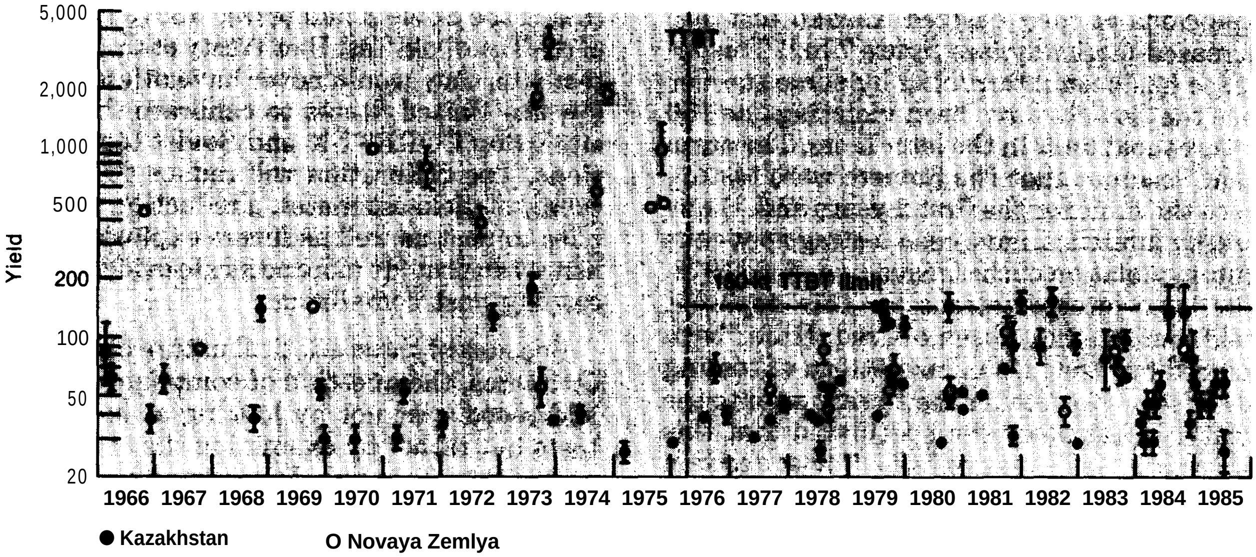


. Kazakhstan O Novaya Zemlya

The m_b versus time for all large Novaya Zemlya and Kazakhstan explosions. It can be seen that a large increase of the maximum yield for explosions at the Eastern Kzazkh test site occurred about 2 years after the Threshold Test Ban Treaty was signed.

SOURCE: T.C. Bache, S.R. Bratt, and L.B. Bache, "P Wave Attenuation m_b Bias, and The Threshold Test Ban Treaty," SAIC-86-1647, submitted to AFGL, March 1966, p. 5.

Figure 7-9.—U.S.S.R. Nuclear Tests 1966-86 According to Sykes and Davis



These yields were calculated by combining P-wave and surface-wave magnitudes and using a bias correction of 0,35. Bars denote the estimated standard deviations of the estimates. The few tests that do appear to have exceeded 150 kt are well within the expected scatter. If a lower bias correction is applied and only P-wave determinations are used, then slightly higher yield estimates will result and additional central values will be greater than 150 kt.

SOURCE: Modified from L.R. Sykes and D.M. Davis, *Scientific America, vol. 258, No.* 1, January 1987, pp. 29-37.

estimation is applied to U.S. tests, approximately the same number of U.S. tests also appear to be above the 150 kt threshold limit. This, however, does not mean that one or the other or both countries have cheated; nor does it defacto mean that seismology is an inadequate method of yield estimation. It is inherent in any method of measurement that if both countries are testing up to the yield limit, the estimated yields of some tests will have central values above the yield limit. Because of the uncertainty of measurements using any method, it is expected that about half the Soviet tests at 150 kt would be measured as slightly above 150 kt and the other half would be measured as slightly below 150 kt.

All of the estimates of Soviet tests are within the 90 percent confidence level that one would expect if the yields were 150 kt or less. Extensive statistical studies have examined the distribution of estimated yields of explosions at Soviet test sites. These studies have concluded that the Soviets are observing a yield limit. The best estimate of that yield limit is that it is consistent with compliance with the 150 kt limit of the Threshold Test Ban Treaty.[13]

[13]Such statistical studies have been carried out extensively by Lawrence Livermore National Laboratory, The conclusion of these studies was reported in open testimony before the Senate Armed Services Committee on Feb. 26, 1987 by Dr. Milo Nordyke, Leader of the Treaty Verification Program.