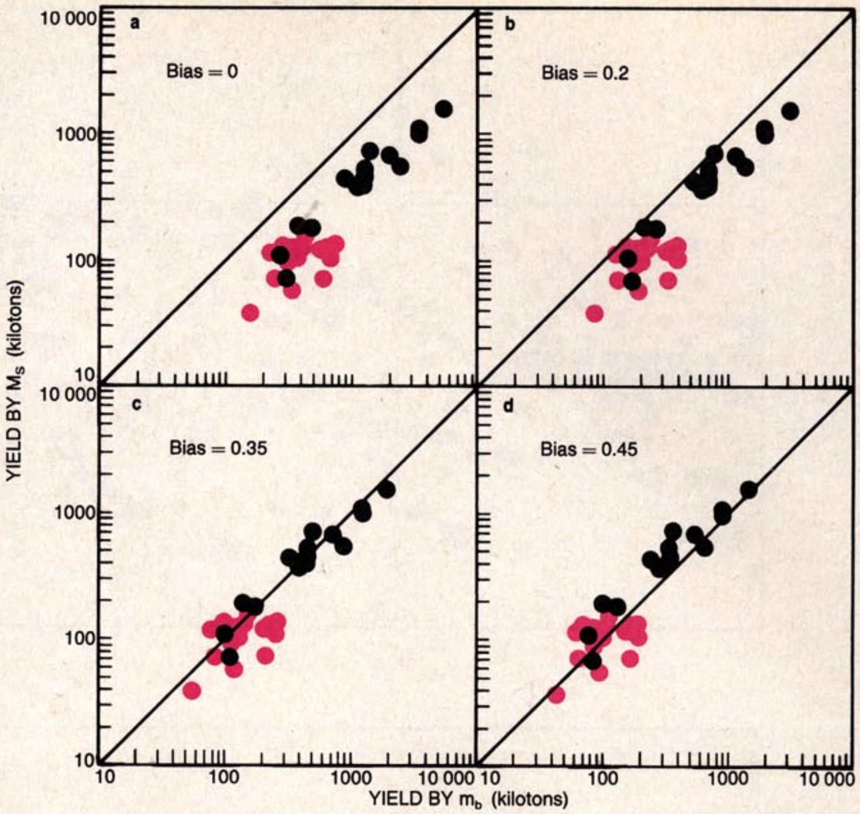
ed data base may well prevent determination of the proper value of the magnitude M_S within 0.1 magnitude units for an explosion with high tectonic release. Some have thought that this problem of marked contamination of the M_S value by the release of tectonic stress seriously perturbed the M_S values obtained for the large post-treaty explosions at Semipalatinsk. It is now generally accepted, however, that there is no evidence for such a perturbation. Contamination of the magnitude M_S by tectonic release is not a problem for any explosions at the Nevada test site if those explosions are observed over a broad range of azimuths.

▶ The velocities P_n of the horizontally traveling seismic waves along the Mohorovičić discontinuity are strongly correlated with the amplitudes of the vertically traveling P waves.[8] The contrast in the velocities P_n between the Soviet test sites and the US test site (8.2–8.3 km/sec versus 7.9 km/sec) confirms a bias in the magnitude m_b of a few tenths between the Soviet and US sites. However, this technique is inadequate to determine the bias in the magnitude m_b at a particular site to the 0.1–0.2 level.

▶ There is an extremely close correlation between the travel times and the amplitude attenuations of P waves through the crust and upper mantle of the Earth. This correlation is associated with variations as great as 0.2 in m_b bias for stations on similar rock in terrains with indistinguishable velocities P_n, and with variations of greater than 0.5 in m_b bias between such stations in different-P_n terrains.[3] To apply this technique of travel time versus amplitude to evaluation of the P-wave bias at Novaya Zemlya and Semipalatinsk relative to the Nevada test site one needs the P-wave arrival times at seismic stations throughout western North America and Eurasia and data from a station at or very near each test site. The Soviets have for several decades published in their seismological bulletins such P-wave arrival times for several standard stations, including one at Semipalatinsk. One can get a detailed estimate of the m_b bias at Semipalatinsk relative to Nevada by this procedure[6]; the resulting value is 0.45 ± 0.02. Unfortunately, there were no Soviet stations near enough to Novaya Zemlya to allow an equally accurate estimate of P-wave magnitude bias there by this technique. Note that two totally separate procedures for estimating the m_b bias between Semipalatinsk and Nevada—M_S and P-wave travel time—agree on a value of about 0.45.

▶ If one knows the shape of the source spectrum of an explosion, one can observe the broadband spectrum at a distance, calculate the attenuation parameter required to reshape the observed spectrum to the source spectrum and then apply this attenuation parameter[9] to the passband used in estimating the magnitude m_b. The problems in this procedure are the assumptions one must make about the details of the source spectrum and the difficulty of uniquely separating elastic and anelastic propagation effects. This technique has reportedly given estimates of an m_b bias of 0.35 for Semipalatinsk. The assumptions in the technique may lead to errors of as much as 0.1 in estimating the correct bias value.

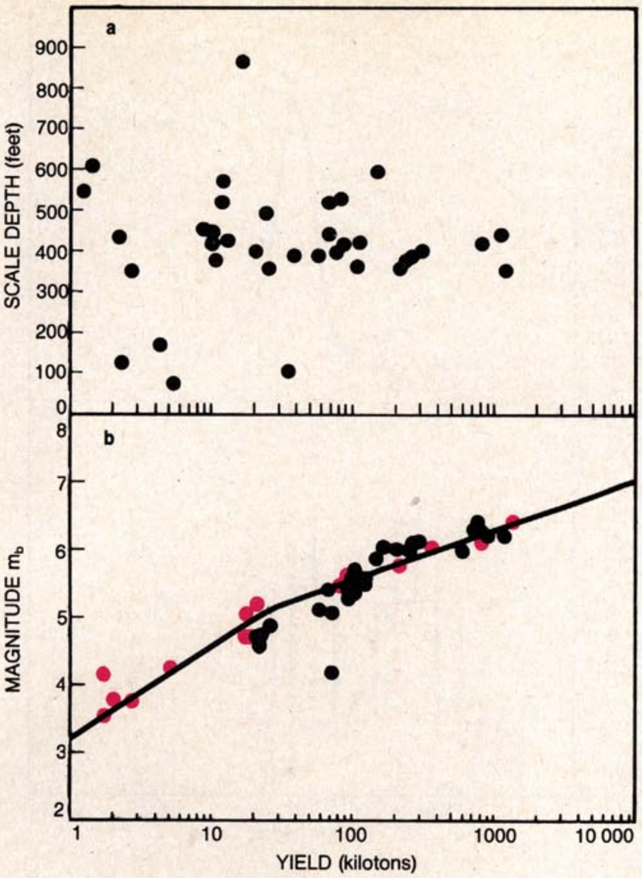
▶ The ideal and direct technique, of course, would be to have amplitude data for P waves of distant earthquakes or explosions as recorded at or very near the Soviet test sites. The Soviets have not made such data available in their seismological bulletins. However, a group from the University of California at San Diego is working in the Semipalatinsk region on a project funded by the Natural Resources Defense Council (see PHYSICS TODAY, August 1986, page 57); one hopes this group will obtain such data.



Calculated yields for 33 Soviet tests with accurately determined seismic magnitudes m_b. The yield of each test was calculated two different ways—by its seismic magnitude m_b and by its seismic magnitude M_S. The two methods give the same results when one assumes a bias to correct for seismological differences between US and Soviet test sites. Black points represent tests at Novaya Zemlya; red points, tests at Semipalatinsk.[4] Figure 3

Recalculating yields. Figures 3b–d present the yields for the 33 events used in figure 3a, recalculated assuming various values of P-wave magnitude or m_b bias for the Soviet test sites relative to the US test site. A value of 0.2 (figure 3b), decreed by bureaucratic fiat within the US government in 1977 in spite of evidence presented at the time that the proper bias value for Semipalatinsk was at least 0.40, is seen to be inadequate to achieve agreement of yield estimates calculated from the magnitudes m_b and M_S. Figure 3c indicates that an m_b bias value of 0.35 quite nicely fits the Novaya Zemlya data, in agreement with Sykes and Cifuentes and the analyses given earlier.[4] A value of 0.45 (figure 3d) gives a better fit to the Semipalatinsk explosions, in agreement with the analysis of P-wave amplitudes versus P-wave travel times discussed above. As pointed out earlier, the appearance of different bias values for the two sites is not surprising, as greater differences in m_b bias were demonstrated many years ago within geotectonic terrains of the US comparable to those at Novaya Zemlya and Semipalatinsk.[3]

Figure 3d indicates that even when we use an m_b bias of 0.45 for Semipala-



Scale depth and magnitude m_b as functions of yield. **a:** Plot of calculated scale depth versus yield for US explosions with announced yields and depths, 1963–76. **b:** Plot of magnitude m_b versus yield for Nevada test site explosions in mesa tuff or granite. Red points denote explosions during the period 1963–76 with announced yields,[13] while black points denote explosions during the period 1971–83 with yields calculated on the basis of announced depths and a scale depth of 450 feet. The linear segment in the high-yield region is given by equation 2. Figure 4

tinsk, the several high-yield events since 1978 have calculated yields with a mean value of about 175 kilotons and maximum and minimum values of about 195 and 155 kilotons. The figure suggests that either the set of five large explosions with calculated yields greater than 150 kt (the five rightmost crosses in each frame of figure 3) were actually each somewhat greater than 150 kt, that a greater m_b bias value is required or that some other factors such as rock properties or slight errrors in the yield-vs-magnitude curves slightly perturbed the m_b value. That the calculated yields are slightly above the 150-kt limit therefore does not necessarily mean cheating by the Soviets. (The standard deviation of the mean m_b value of these explosions is 0.018, meaning that the standard deviation of the yield estimates is about 10 kt, assuming correctness of the yield-vs-mgnitude curves; if all are assumed to be of the same yield, the mean calculated yield is about 175 kt with a standard deviation of 5–10 kt.)

Lawrence Livermore National Laboratory reached a similar interpretation of the seismological data of the Semipalatinsk explosions some years ago. In a report in *The Bulletin of the Atomic Scientists*, Marsh presents quotations from letters by Warren Heckrotte and Michael May of Livermore; in these May states explicitly that internal Livermore documents "did conclude that there was no evidence that the Soviets had cheated on the Threshold Test Ban Treaty."[10] Roger Batzel,[11] the present director of Livermore, reiterated that evaluation in testimony to Congress in 1985.

The analysis of the US and USSR testing programs presented below indicates that the Soviets would accrue no technical advantage by testing at 175 kilotons rather than at 150 kilotons. Although it has not yet been demonstrated, we expect that the explanation for these higher-yield tests will probably be found in seismological details such as those suggested above.

Thus several simple, direct and totally independent seismological procedures for estimating yields of Soviet explosions agree on a positive P-wave magnitude bias value of 0.35 or greater for both Novaya Zemlya and Semipalatinsk relative to Nevada, while the procedures we deem most accurate indicate a P-wave magnitude bias of 0.45 for Semipalatinsk. In this regard it is worth quoting from a presentation to Congress by Paul G. Richards, a geophysicist at Columbia University's Lamont–Doherty Geological Observatory, who had reviewed all available information.[12] Discussing the adequacy of then available data and analyses for the quantitative evaluation of the P-wave magnitude bias problem, Richards first quoted from a 1977 report by Evernden[6] and then stated that "Although in some details the scientific argument has required slight revision in light of later work, the main conclusion is [essentially that?] adopted recently when the US government's [position?] was revised." The phrases in brackets are our guesses of the words that the government censored before releasing Richards's testimony in unclassified form.

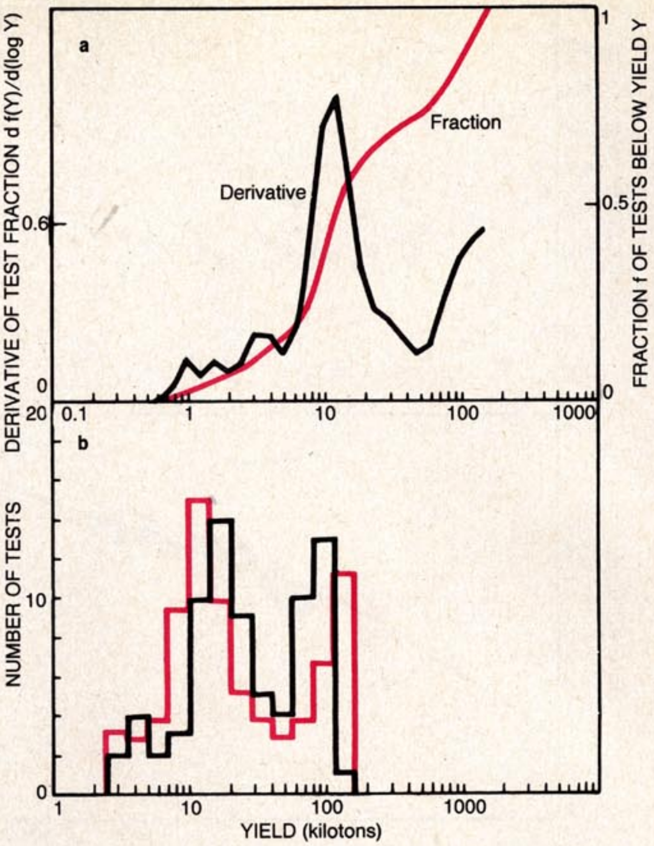
US testing program

To use an indirect procedure to estimate the yields of Soviet nuclear tests, it is necessary to have a reasonably accurate picture of the entire US test program. The yields of only a few US explosions at the Nevada test site have been declassified. (For a complete list of these events, see *Nuclear Weapons Databook*, Natural Resources Defense Council, Washington, DC, 1984.) However, the government has announced the depths of nearly all the Nevada explosions. Figure 4a, a plot of data for Nevada events with announced yields and depths, indicates a strong tendency to detonate explosions at a scale depth D_s of 400–450 feet, based on the relation

$$\text{Depth(feet)} = D_s\,[\text{yield(kt)}]^{1/3} \qquad (3)$$

Figure 4b also suggests use of a scale depth of 450 feet. The red points on Figure 4b are data for explosions in mesa tuff or granite for which the government announced yields; the m_b values for these explosions are as published by Evernden and Archambeau[5] or in the bulletins of the National Earthquake Information Service.[13] The line drawn through these points is somewhat different from that published in Evernden and Archambeau, because the high-yield curve of figure 4b has the added contraint imposed by the two explosions near 90 kilotons, code-named Miniata and Starwort. The bend in the curve indicates[5] a change in the frequency spectrum for yields exceeding about 50 kilotons. The black points in figure 4b are based upon m_b values published by NEIS for explosions in mesa tuff or granite between 1971 and 1983, with the "yields" for these events being based on their announced depths, use of equation 3 and a scale depth of 450 feet. The agreement of the black points with the curve based on the red points indicates that usual US practice in recent years certainly has been to use a scale depth of close to 450 feet. The single black point far below the other data implies either a greatly over-buried explosion—one much deeper than the 450-foot scale depth—or an explosion that did not go off at the expected yield—one with a magnitude m_b lower than expected.

Figures 5a and 5b are yet another demonstration that the United States uses a scale depth of approximately 450 feet. The black curve of figure 5a is the plot of $df(Y)/d\log(Y)$ published by Ray Kidder[14] of Livermore for test yields at the Nevada test site during 1980–84. Here $f(Y)$ is the fraction of tests whose yields were Y kilotons or less. Kidder's curve is based on the actual yields. The red curve in figure 5a is the function $f(Y)$ derived by integrating Kidder's curve. The red histogram of figure 5b is derived from the function $f(Y)$ of figure 5a, while the black histogram is derived from US tests during the same period by using published depths of explosions, a scale depth of 450 feet and equation 3. The vertical scale of the red histogram is adjusted to imply the same number of tests as the black histogram. The two patterns of figure 5b are different in detail but basically very similar. Though the curves have peaks of somewhat different shape, they do show nearly the same number of high- and low-yield tests. The agreement is adequate to support the conclusion that explosions at the Nevada test site are routinely detonated at a scale depth very near 450 feet. In the following discussion, interpretation of the US testing pattern is based on a scale depth of 450 feet for all explosions. We do not mean to imply that one can accurately estimate the yield of each US test in this manner; it does, however, yield a close estimate of the pattern of US testing.



Yield distribution of explosions[4] at the Nevada test site, 1980–84. The black curve in **a** is the published function $df(Y)/d(\log Y)$. The red curve, obtained by integration, is the implied fraction $f(Y)$ of tests with yields at or below Y kilotons. The black curve in **b** is a histogram of yields calculated from announced depths when one assumes a scale depth of 450 feet for all explosions. The red curve in **b** is a histogram based on the red curve in **a**. This histogram and those in subsequent figures are terminated at 2.5 kilotons with yield-bin boundaries increasing by a factor of $2^{1/2}$. Figure 5

USSR testing program

Non-seismological arguments based on the above discussion of the US testing program and on various other considerations all indicate a high bias in the magnitudes m_b for Semipalatinsk and Novaya Zemlya relative to the Nevada test site, with an associated lack of regional variation of the magnitudes M_S. Statements both old and recent by people connected with the US weapons laboratories provide the bases for these arguments.

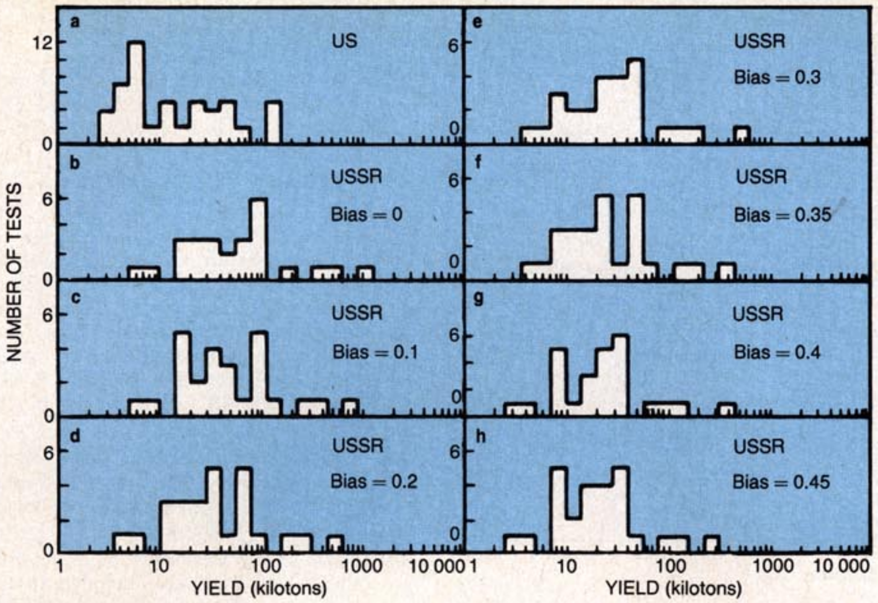
An argument for a large m_b bias between Semipalatinsk and Nevada was presented by weapons designers 20 or so years ago—before there was a seismological understanding of the bias problem. Recent statements in the open literature permit us to present that argument, which is as valid today as it was originally.

To begin with, it has often been stated that nuclear warheads are characterized by having "primary" and "secondary" explosive devices, both of them nuclear. This is confirmed in a 1983 Lawrence Livermore bulletin, which states that "x-rays produced during the nuclear explosion of the primary transfer energy to compress and ignite thermonuclear fuel contained in the secondary."[15] It is the testing of the primary that is critical to the design of a nuclear weapon, as Richard L. Wagner Jr, then assistant to the Secretary of Defense for atomic energy, stated in 1986: "The primary design is the sort of bellwether of whether it will work . . . we can test all primary designs which are at a lower yield, thereby giving us continued reasonable assurance that the design will work at full yield."[16] Wagner was speaking within the context of the Threshold Test Ban Treaty, which, he noted, allows one to test "the primary or a combination of the primary and an altered secondary, which would not exceed the threshold."

One can infer from a comment by Harold Agnew in a letter to Congressman Jack Kemp that testing at a yield of about 10 kilotons or somewhat more is of particular importance to a rational test program[17]: "I don't believe testing below five or ten kilotons can do much to improve (as compared to maintaining) strategic posture." As we will see, the distinction between "improve" and "maintaining" corresponds to that between testing secondaries or only primaries. Discussing the effect that a comprehensive test ban treaty would have on weapons design, Agnew said, "The military significance to either the USSR or the USA of conducting clandestine tests below 5 or 10 kilotons is *per se* of relatively little importance today."

Figure 6a shows the yields of US tests during 1963–65, the first three years of underground testing, calculated assuming a scale depth of 450 feet. The histogram has peaks at a few kilotons and indicates an almost uniform level of testing from 10 to 56 kilotons. The testing at low yields is almost certainly related to the development of tactical nuclear weapons and primaries; note in figure 2b the concentration of low-yield tests in the very early years of the underground program.

During the years 1965–70, as US seismologists were establishing that it is possible to identify the seismic waves of underground explosions down to magnitudes m_b of around 4.75 (corresponding to yields of 10–15 kilotons in hard rock, as figure 4b indicates), representatives of the weapons laboratories repeatedly depreciated these accomplishments as being of no significance to a test-ban-monitoring environment: They stated that it is possible to scale up to full yield without testing above 10–20 kilotons. The implications of that repeated statement agree with the supposition that primaries have a maximum yield of 10–20 kilotons and with Wagner's statement about the



Histograms of yields for the US and Soviet test programs during the first three years of underground tests. Yields for US tests during 1963–65 were calculated using announced depths and a scale depth of 450 feet. Yields for Soviet tests during 1964–66 were calculated using National Earthquake Information Service magnitude values, equation 2 and the indicated biases in the magnitudes m_b. Figure 6

possibility of scaling up from the testing of primaries or of primaries and degraded secondaries.[16]

Figures 6b–h are based on the first three years of Soviet underground testing. Figure 6b, which assumes no bias in the magnitude m_b, indicates that there were no Soviet tests between 10 and 14 kilotons and that the highest peak in activity was at 80–112 kilotons. This pattern is drastically different from the US pattern in figure 6a and implies the unlikely conclusion that the Soviets were testing secondaries and relatively few primaries or that they were using 100-kt primaries. However, as the P-wave magnitude bias increases from figure 6b to figure 6h, the calculated pattern of Soviet testing becomes very similar to the US pattern. Under the obvious constraint that physical and military requirements dictate the character of testing patterns, figures 6f–h imply an m_b bias distinctly greater than 0.35 at Semipalatinsk.

Further study of the patterns of testing by the US and the USSR strengthens these conclusions as well as leading to some interesting interpretations. Figure 2b presents the US testing pattern for 1963–84, based on a scale depth of 450 feet and the use of all events for which a depth was announced. Each tick mark along the horizontal axis indicates ten tests. The vertical line demarcates 31 March 1976, the acceptance date of the 150-kt limit of the Threshold Test Ban Treaty. Note the burst of high-yield testing just prior to the treaty and the absence of tests exceeding 150 kt since the treaty. (The magnitudes m_b of these events confirm them to be less than 150 kt.) The concentration of low-yield tests in the mid- to late 1960s is obvious.

Figure 2a gives the pattern of Soviet testing during 1964–85, expressed in magnitudes m_b as published by the National Earthquake Information Service. The maximum magnitude m_b of 5.8 immediately after the treaty and the subsequent rise to 6.2 are clearly visible. This rise at Semipalatinsk and confusion about its proper interpretation triggered the now largely resolved intragovernmental disputes about the magnitude bias in 1976.

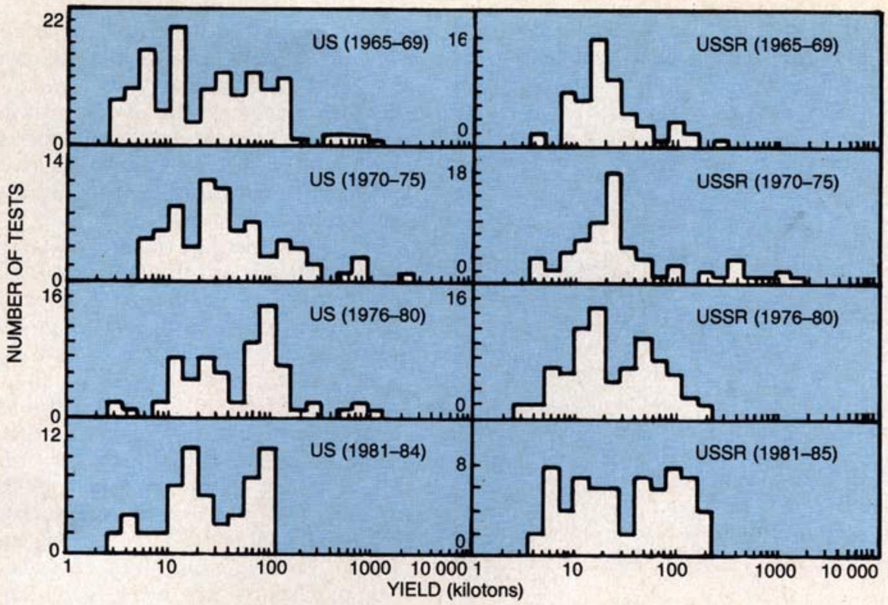
Sykes has pointed out that study of the Soviet pattern of high-yield tests is yet another means of demonstrating a large bias in the magnitudes m_b at Novaya Zemlya.[18] He notes that between 1973 and 1976 the USSR deployed five strategic systems, including the MIRVed versions of the SS-17, SS-18 and SS-19, with warhead yields beteen 300 and 600 kilotons according to CIA National Intelligence Estimates quoted by Peter Samuel.[19] Samuel's statements make it clear that these yield estimates are based on non-seismological criteria. Samuel says that if one uses the official value of the m_b bias, presumably 0.2, then no Soviet tests prior to 1976 have had yields in the 300–600-kt range. He concludes that either the methods of determining yields from seismic data are incorrect or the yields of Soviet warheads given by the National Intelligence Estimates are wrong.

Let us assume that the Soviets tested these warheads at full yield. Figure 2a shows there to have been five explosions prior to 1976 in the m_b range 6.4–6.5, all of them at Novaya Zemlya and of very similar yield. Use of an assumed m_b bias of 0.2 leads to the conclusion that there was little testing in the range 300–600 kt, but that there were five tests in the range 600–800 kt, a yield range with no known purpose for Soviet warheads. Using an m_b bias of 0.35, however, one finds the set of five explosions to have calculated yields of 400–500 kt, while a bias of 0.4 gives yields of 300–400 kt for these explosions. This adjustment of calculated yields by use of the seismologically correct m_b bias brings the seismological estimates and the National Intelligence Estimates into full agreement. The National Intelligence Estimates thus give another demonstration of a P-wave magnitude bias at Novaya Zemlya of 0.35–0.40 as shown in figure 3.

The impact of using the correct m_b bias to evaluate the Soviet test program is succinctly indicated by comparing the aggregate explosive yields of that program obtained assuming no magnitude bias and using the proper biases at Semipalatinsk and Novaya Zemlya. Use of zero m_b bias leads to a calculated aggregate yield of 59 megatons for all Soviet underground tests, while use of the proper m_b biases lowers the estimate to 19 megatons.

Historical comparison

Figure 7 shows histograms of the patterns of testing by the US and USSR over the years. The figure separates the testing programs into four time intervals. In the US program, the years 1965–74 were characterized by development of sophisticated warheads, with little further advance in design in later years. One can interpret the nearly uniform level of testing between 20 and 1000 kilotons during this period as a reflection of the development of sophisticated secondaries. Contrast this US pattern with that of the USSR during the same years. With the assumed bias of 0.45 at Semipalatinsk, the site of all these tests, the Soviet testing pattern shows marked peaking at 15–30 kilotons. This is the expected pattern if primaries were of those yields and if the test program included mostly primaries, with full-yield weapons requiring little further



Evolution of US and Soviet underground testing programs. Some US test yields in the period 1976–80 exceed 150 kilotons because that period brackets the acceptance of the treaty limit. The absence of US test yields exceeding 113 kilotons in the period 1981–84 may reflect use of a scale depth of slightly less than 450 feet for the larger explosions of this period. As discussed in the text, yields of the largest Soviet tests since the treaty are calculated as 170 $\pm$ 20 kilotons; most of these explosions thus fall in the yield bin 160–226 kt. The histograms assume a 450-ft scale depth for US tests and a magnitude bias of 0.45 for Soviet tests. Figure 7

testing as discussed above.

Comparison of the US and Soviet testing patterns for 1981–85 suggests that both countries do indeed use primaries with maximum yields of 10–30 kilotons. Further, inspection of the periods 1976–80 and 1981–85 indicates a marked change in Soviet testing; these patterns look very much like the US 1965–69 and 1976–80 patterns, respectively, lacking the high-yield events barred by treaty. Thus it seems reasonable to conclude that the Soviet testing program and stockpile designs have been proceeding toward greater sophistication along the lines pursued by the US 5 to 10 years earlier. Arguments for the greater reliability and slower degradation of Soviet weapons under a comprehensive or low-threshold test ban treaty, based as they are on the presumed simplicity of Soviet warheads, may not be as solidly based as frequently implied.[20] It is also not necessarily true that any degradation of the nuclear weapons stockpile need occur under such treaties.[21]

The multiplicity of seismological arguments demonstrating a large bias in the P-wave magnitude m_b between the Soviet test sites and the Nevada test site—arguments extant in the seismological literature since the early 1970s—should finally be accepted as definitive. The only remaining issue is the exact value of the bias at any particular point, as there is marked variation in bias even within terrain that appears uniform by superficial analysis.

References

1. For an introduction to seismological definitions relevant to nuclear tests, see L. Sykes, J. Evernden, Sci. Am., October 1982, p. 47; J. Evernden, Bull. At. Sci., March 1985, p. 9.
2. J. Evernden, J. Filson, J. Geophy. Res. **76**, 3303 (1971).
3. J. Evernden, D. Clark, Phys. Earth Planet. Inter. **4**, 1, 24 (1970).
4. L. Sykes, I. Cifuentes, Proc. Natl. Acad. Sci. USA **81**, 1922 (1984).
5. J. Evernden, C. Archambeau, in *Technical Means of Verification of Compliance with Arms Control Treaties*, K. Tsipis, ed., Pergamon, New York (1986), ch. 16.
6. J. Evernden, *Regional Bias in Magnitude Versus Yield Measurements: Its Explanation and Modes of Evaluation*, unclassified report submitted to Arms Control and Disarmament Agency, Washington, DC (1977). This report contains the most expansive discussion and supporting list of references available on the numerous geophysical parameters that correlate with bias in the magnitudes m_b and that explain its fundamental cause; the report also discusses the lack of regional bias in the magnitudes M_S.
7. C. Archambeau, Geophys. J. R. Astron. Soc. **29**, 329 (1972). C. Archambeau, C. Sammis, Rev. Geophys. **8**, 473 (1970). J. Evernden, C. Archambeau, E. Cranswick, Rev. Geophys. **24**, 143 (1986).
8. P. Marshall, D. Springer, H. Rodean, Geophys. J. R. Astron. Soc. **57**, 609 (1979).
9. Z. A. Der, T. W. McElfresh, Bull. Seismol. Soc. Am. **70**, 921 (1980). Z. A. Der, A. C. Lees, M. R. Marshall, EOS Trans. **67**, 302 (1986).
10. G. E. Marsh, Bull. At. Sci., March 1983, p. 4.
11. R. Batzel, in *Department of Energy Fiscal Year 1986 Authorization for Defense Programs*, testimony before the Subcommittee on Strategic and Theatre Nuclear Forces of the Senate Armed Services Committee, 99th Congress, 1st session, 14 March 1985; available in Senate Hearing 99–485, US Govt. Print. Off. (1986), p. 169.
12. P. Richards, presentation to the House Permanent Select Committee on Intelligence, Subcommittee on Oversight and Evaluation, 6 May 1986.
13. Depths of US explosions as announced by AEC or DOE are included in the seismological bulletins issued by the National Earthquake Information Service of the US Geological Survey. This article uses the magnitudes m_b calculated by the NEIS and published in its bulletins.
14. R. Kidder, oral presentation at DOE-sponsored Workshop on Cavity Decoupling, 29 July 1985, document no. UCRL-93194, Lawrence Livermore National Laboratory, Livermore, Calif. (August 1985); reprinted in Public Interest Report (Federation of American Scientists, Washington, DC), September 1985, p. 1.
15. *LLNL Classification Bulletin WNP-45A* (supplement), Lawrence Livermore National Laboratory, Livermore, Calif. (28 June 1983).
16. R. L. Wagner Jr, in *Review of Arms Control and Disarmament Activities, 99th Congress, 1st Session*, House Armed Services Committee report no. 99-18, US Govt. Print. Off. (1986), p. 115.
17. H. M. Agnew, letter to J. Kemp, 19 April 1977, in *Effects of a Comprehensive Test Ban Treaty on United States National Security Interests*, House Armed Services Committee report no. 95-89, US Govt. Print. Off. (1978), p. 192.
18. L. Sykes, letter to D. B. Fascell, chairman of House Foreign Affairs Committee, 30 August 1985.
19. P. Samuel, Defense Week, 5 August 1985, p. 1.
20. J. K. Landauer, *National Security and the Comprehensive Test Ban*, document no. UCRL-84848, Lawrence Livermore National Laboratory, Livermore, Calif. (August 1980).
21. R. E. Kidder, *Evaluation of the 1983 Rosengren Report from the Point of View of a Comprehensive Test Ban*, document no. UCID-20804, Lawrence Livermore National Laboratory, Livermore, Calif. (1986). R. E. Kidder, *Stockpile Reliability and Nuclear Test Bans: Response to J. W. Rosengren's Defense of His 1983 Report*, document no. UCIS-20990, Lawrence Livermore National Laboratory, Livermore, Calif. (February 1987). □