Chapter 1

Executive Summary

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Technologies that were originally developed to study earthquakes may now enable the United States to verify a treaty with the Soviet Union to further limit the testing of nuclear weapons.

INTRODUCTION

Seismology now provides a means to monitor underground nuclear explosions down to low yields, even when strenuous attempts are made to evade the monitoring system. By doing so, seismology plays a central role in verifying arms control agreements that limit the testing of nuclear weapons. Seismology, however, is like any other technology: it has both strengths and limitations. If the capabilities of seismic monitoring are to be fully realized, it is necessary to understand both how the strengths can be used and how the limitations can be avoided.

To a great extent, the capabilities of any given seismic monitoring network are determined by how the monitoring task is approached and what supplementary provisions are negotiated within the treaty. If agreements can be negotiated to reduce uncertainty, then seismology can be very effective and extremely low yields could be monitored with high confidence.

This report addresses two key questions:

1. down to what size explosion can underground testing be seismically monitored with high confidence, and
2. how accurately can the yields of underground explosions be measured seismically?

The answers to these questions provide the technical information that lies at the heart of the political debate *over:*

1. how low a threshold test ban treaty with the Soviet Union we could verify,
2. whether the 1976 Threshold Test Ban Treaty is verifiable, and
3. whether the Soviet Union has complied with present testing restrictions.

Seismic monitoring as discussed in this study is evaluated without specific references to the particular treaty regime to which it is to apply. There will always be some limit to the capability of any given monitoring network, and hence there will always be a threshold below which a seismic network could not monitor with high confidence. Consequently, should a total test ban be enacted there will be a very low threshold below which seismic methods cannot provide high confidence monitoring. Such a treaty could still be considered to be in the national interest if, taking both seismic and nonseismic verification methods into account, the significance of undetected violations (if they were to occur) would be outweighed by the benefits of such a treaty.

THE TEST BAN DEBATE

Test ban treaties are a seemingly simple apreach to nuclear arms control, yet their impact is complex and multi-faceted. The decision as to whether a given test ban treaty is in our overall national interest is dependent on many questions concerning its effects. Disadvantages in one area must be weighed against advantages in another. Consequently, all aspects of a new treaty must be considered together and the cumulative impact evaluated in terms of a balance with the Soviet Union. Finally, the total net assessment of the effects of a

Photo credit: Department of Energy

Signal cables and test device being lowered down test hole.

treaty on our national security must be weighed against the alternative: no treaty.

One's opinion about the effects of a test ban, and thus its desirability, is largely dependent on one's philosophical position about the role of a nuclear deterrent and the extent to which arms control can contribute to national security. It is perhaps because test ban treaties go to the very heart of nuclear weapons policy that the debate over them remains unresolved. Three decades of negotiation between the United

States and the U.S.S.R. have produced only three limitation treaties, two of which remain unratified:

1. 1963 Limited Nuclear Test Ban Treaty (LTBT). This treaty bans nuclear explosions in the atmosphere, in outer space, and under water. It was signed by the United States and the U.S.S.R. on August 5, 1963 and has been in effect since October 10, 1963. Over 100 other countries have also signed this treaty.
2. 1974 Threshold Test Ban Treaty (TTBT). This treaty restricts the testing of underground nuclear weapons to yields no greater than 150 kilotons (kt). It was signed by the United States and the U.S.S.R. on July 3,1974. Although the TTBT has yet to receive the consent of the U.S. Senate, both nations consider themselves obligated to adhere to it.
3. 1976 Peaceful Nuclear Explosions Treaty (PNET). This treaty is a complement to the TTBT and restricts individual peaceful nuclear explosions (PNEs) to yields no greater than 150 kt, and aggregate yields in a salvo to no greater than 1500 kt. It was signed by the United States and the U.S.S.R. on May 28,1976. Although PNET has yet to receive the consent of the U.S. Senate, both nations consider themselves obligated to adhere to it.

Nuclear explosions compliant with these treaties can only be conducted by the United and the U.S.S.R. underground, at specific test sites (unless a PNE), and with yields no greater than 150 kt. Although they have had important positive environmental and arms control impacts, these treaties have not prevented the development of new types of warheads and bombs. For this reason, public interest in a complete test ban or a much lower threshold remains strong, and each year a number of proposals continue to be brought before the Congress to limit further the testing of nuclear weapons.

THE MEANING OF VERIFICATION

For the United States, the main national security benefits derived from test limitation treaties are a result of the Soviet Union being similarly restricted. In considering agreements that bear on such vital matters as nuclear weapons development, each country usually assumes as a cautious working hypothesis that the other parties would cheat if they were sufficiently confident that they would not be caught. Verification—the process of confirming compliance and detecting violations if they occur—is therefore central to the value of any such treaty.

"To verify" means to establish truth or accuracy. Yet in the arena of arms control, the process of verification is political as well as technical. It is political because the degree of verification needed is based upon one's perception of the benefits of a treaty compared with one's perception of its disadvantages and the likelihood of violations. No treaty can be considered to be either verifiable or unverifiable without such a value judgment. Moreover, this judgment is complex because it requires not only an understanding of the capabilities of the monitoring systems, but also an assessment as to what is an acceptable level of risk, and a decision as to what should constitute significant noncompliance. Consequently, people with differing perspectives on the role of nuclear weapons in national security and on the motivations of Soviet leadership will differ on the level of verification required.[1]

[1]This issue is discussed further in chapter 2, *Seismic Verification in the Context of National Security.*

ASPECTS OF MONITORING UNDERGROUND NUCLEAR EXPLOSIONS

Like earthquakes, the force of an underground nuclear explosion creates seismic waves that travel through the Earth. A seismic monitoring network must be able both to detect and to *identify* seismic signals. Detection consists of recognizing that a seismic event has occurred and locating the source of the seismic signals. *Identification* involves determining whether the source was a nuclear explosion. In the case of a threshold treaty, the monitoring network must also be able to estimate the yield of the explosion from the seismic signal to determine if it is within the limit of the treaty. All of this must be done with a capability that can be demonstrated to adequately defeat any credible attempt to evade the monitoring network.

If the seismic signals from explosions are not deliberately obscured or reduced by special efforts, seismic networks would be capable of de*tecting* and identify with confidence nuclear explosions with yields below 1 kt. What stops this capability from being directly translated into a monitoring threshold is the requirement that the monitoring network be able to accomplish detection and identification with high confidence in spite of any credible evasion scenario for concealing or reducing the seismic signal from a test explosion.

Demonstrating that the monitoring capability meets this requirement becomes complex at lower yields. As the size of the explosion becomes smaller:

- there are more opportunities for evading the monitoring network,
- there are more earthquakes and industrial explosions from which such small clandestine explosions need to be distinguished, and
- there are more factors that can strongly influence the seismic signal.

The cumulative effect is that the lower the yield, the more difficult the task of monitoring against possible evasion scenarios.

The threat of evasion can be greatly reduced by negotiating within a treaty various cooperative monitoring arrangements and testing restrictions. However, there will eventually be a yield below which the uncertainty of any monitoring regime will increase significantly. The point at which the uncertainties of the monitoring system no longer permit adequate verification is a political judgment of the point at which the risks of the treaty outweigh the benefits.

Determining the credibility of various evasion methods requires subjective judgments about levels of motivation and risk as well as more objective technical assessments of the capability of the monitoring system. To separate the technical capabilities from the subjective judgments, we will first describe our capability to detect and identify seismic events and then will show how this capability is limited by various possible evasion methods. All considerations are then combined to address the summary question: *How low can we go?*

Detecting Seismic Events

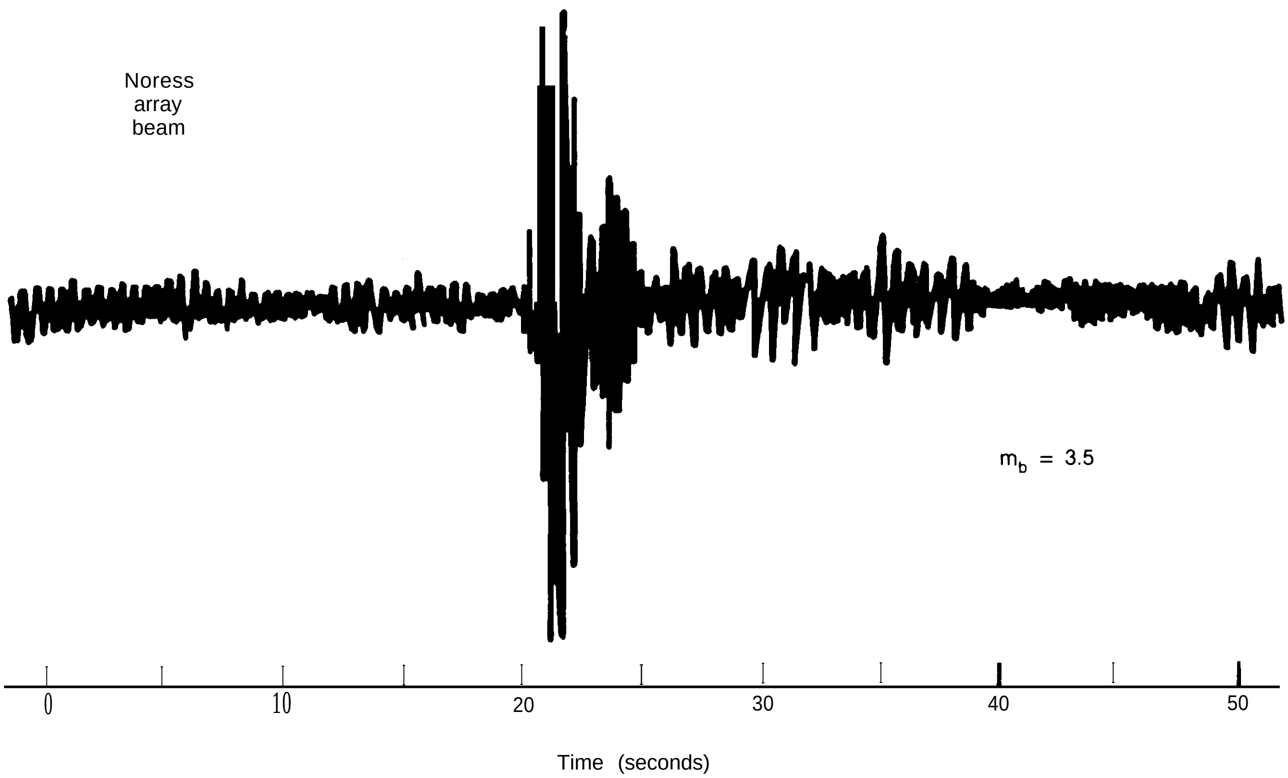
The first requirement of a seismic network is that it be capable of detecting a seismic event. If the Earth were perfectly quiet, this would be easy. Modem seismometers are highly sophisticated and can detect remarkably small motions. Limitations are due not to the inherent sensitivity of the instrument but rather to phenomena such as wind, ocean waves, and even rush hour traffic. All of these processes cause ground vibrations that are sensed by seismometers and recorded as small-scale background motion, collectively referred to as "noise." Seismic networks, consisting of groups of instruments, are designed to distinguish events like earthquakes and explosions from this ever-present background noise. The extent to which a seismic network is capable of detecting such events is dependent on many factors. Of particular importance are the types of seismic stations used, the number and distribution of the stations, the amount of background noise at the site locations, and the efficiency with which seismic waves travel from the source to the receiving station through the surrounding geologic area.

Detecting seismic events can be accomplished with high certainty down to extremely small yields. A hypothetical seismic network with stations only outside the Soviet Union would be capable of detecting well-coupled[2] explosions with yields below 1 kt anywhere within the Soviet Union and would be able to detect even smaller events in selected regions. The existing seismic array in Norway, for example, has easily detected Soviet explosions with yields of a fraction of a kt conducted 3,800 kilometers away at the Soviet test site in Eastern Kazakhstan (figure l-l).

Seismic stations within the Soviet Union would further improve the detection capability of a network. In principle, almost any desired signal *detection* level could be achieved within the Soviet Union if a sufficient number of internal stations were deployed. In this sense, the detection of seismic events does not provide a barrier for monitoring even the lowest threshold treaties. From a monitoring stand-

2 A "well-coupled" explosion is one where the energy is well transmitted from the explosion to the surrounding rock.

Figure 1-1 .-Signal From Semipalatinsk



Seismic signal from a 0.25 kt explosion at the Soviet test site near Semipalatinsk. Recorded 3,800 km away at the NORESS seismic array in Norway on July 11, 1985. The signal to noise ratio is about 30 indicating that much smaller explosions could be detected even at this great distance.

SOURCE: R.W. Alewire Ill, "Seismic Sensing of Soviet Tests," *Defense 85,* December 1985, pp. 11-21.

point, stations within the Soviet Union are more important for improving *identification* capabilities than for further reduction of the already low detection threshold.

Identifying Seismic Events as Nuclear Explosions

Once a seismic signal has been detected, the next task is to determine whether it was created by a nuclear explosion. Seismic signals are generated not only by nuclear explosions, but also by natural earthquakes, rockbursts in mines, and chemical explosions conducted for mining, quarry blasting, and construction.

Every day there are many earthquakes around the globe whose seismic signals are the same size as those of potential underground nuclear explosions. Several methods can be applied to differentiate earthquakes from underground nuclear explosions. Note, however, that no one method is completely reliable. It is the set of different identification methods taken as a whole and applied in a systematic fashion that is assessed when summaries on capability are given. In this sense, identification is a "winnowing" process.

The most basic method of identification is to use the location and the depth of the event. Over 90 percent of all seismic events in the U.S.S.R. can be classified as earthquakes simply because they are either too deep or not in a plausible location for a nuclear explosion. For seismic events that are in a location and at a

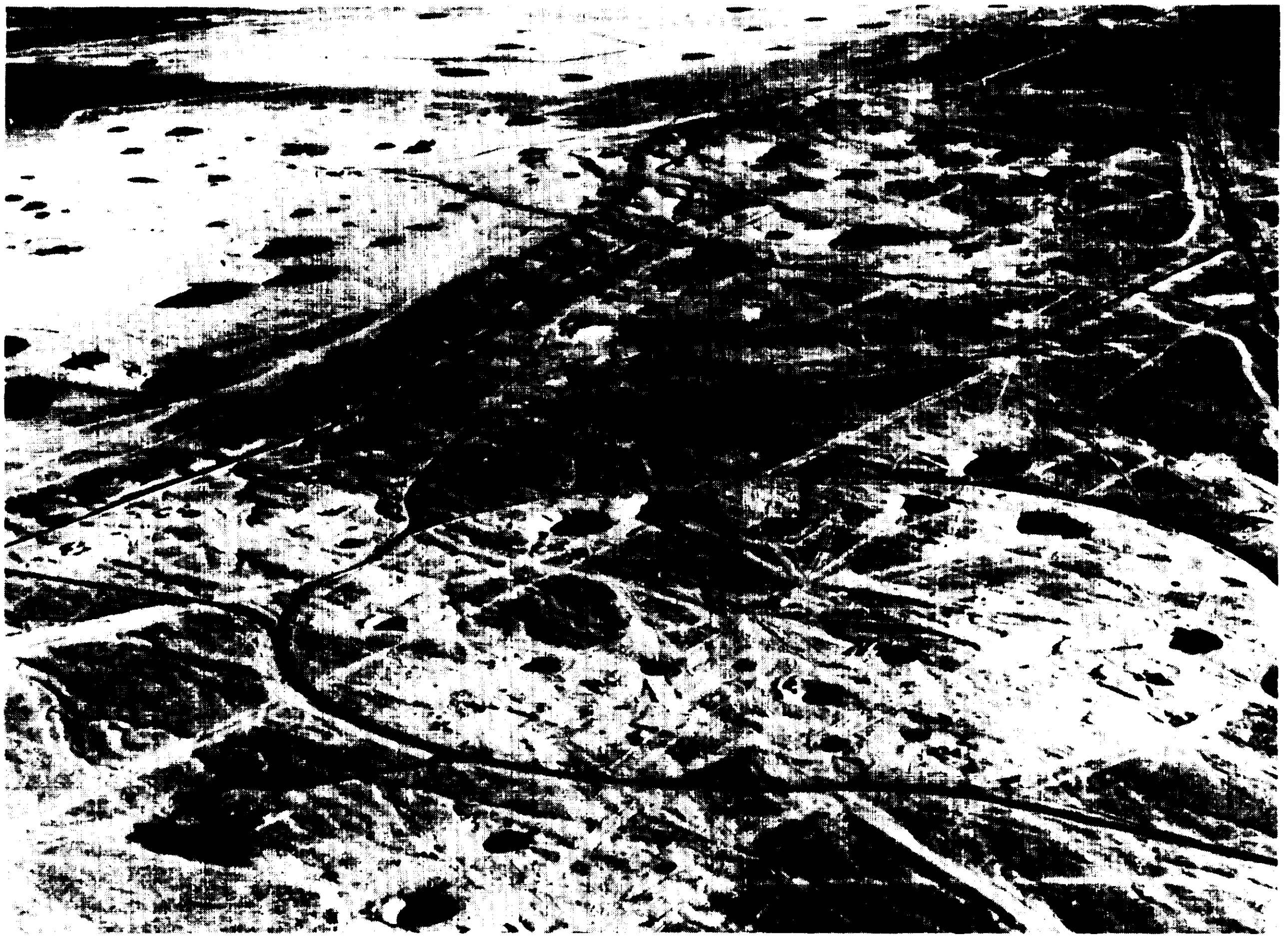


Photo credit: Department of Energy

Craters formed by cavity collapse in Yucca Flat, Nevada Test Site.

depth that could bean explosion, other methods of discrimination based on physical differences between earthquakes and explosions are used.

When a nuclear device explodes underground, it applies uniform pressure to the walls of the cavity it creates. As a result, explosions are seen seismically as highly concentrated sources of *compressional waves,* sent out with approximately the same strength in all directions from the point of the detonated device. An earthquake, on the other hand, occurs when two blocks of the Earth's crust slip past each other along a fault. An earthquake generates *shear waves* from all parts of the fault that rupture.

These fundamental differences between earthquakes and explosions are often exhibited in their seismic signals. As a result, seismologists have been able to develop a series of methods to differentiate the two sources based on the different types of seismic waves they create. The combination of all methods, when applied in a comprehensive approach, can differentiate with high confidence between explosions, down to low yields, and earthquakes.

As the size of the seismic events gets smaller, nuclear explosions must be distinguished not only from earthquakes, but also from other kinds of explosions. Industrial chemical explosions (e.g. in a quarry operation) pose a particularly difficult problem because their seismic signals have physical characteristics similar to those of nuclear explosions. Consequently, the seismic methods that are routinely used to differentiate earthquakes from explosions cannot distinguish between some legitimate chemical explosions for mining purposes and a clandestine nuclear test explosion. Fortunately, industrial explosions in the range of 1 to 10 kt are rare (less than one a year). Large explosions are usually ripple fired so as to minimize ground vibration and fracture rock more efficiently. Ripple firing is often accomplished with bursts spaced about 0.2 seconds apart over a duration of about a second. Recent work suggests that this ripple-firing has an identifiable signature apparent in the observed seismic signals, and therefore can be used to identify such chemical explosions. However, the absence of evidence for ripple firing cannot be taken as evidence that the event is not a chemical explosion. Because of the size considera-tion, industrial explosions are not an identification problem for normal nuclear explosions above 1 kt. The difficulty, as we will see later, comes in distinguishing between a small *decoupled* nuclear test and a large salvo-fired chemical explosion. This difficulty can be limited through such treaty provisions as options for inspections and constraints on chemical explosions.[3]

Because a seismic *signal* must be clearly detected before it can be identified, the threshold for identification will always be greater than the threshold for detection. As described in the previous section, however, the detection threshold is quite low. Correspondingly, even a hypothetical network consisting of stations only *outside* the Soviet Union would be capable of *identifying* seismic events with magnitudes corresponding to about 1 kt *if* no attempts were made to evade the monitoring system.[4] Seismic stations within the Soviet Union would further improve the identification capability of a network.

It has been argued that the use of high frequency seismic data will greatly improve our capability to detect and identify low-yield nuclear explosions.[5,6] Recent experiments conducted by the Natural Resources Defense Council together with the Soviet Academy of Sciences are beginning to provide high frequency seismic data from within the Soviet Union that shows clear recordings of small explosions (see box l-A). There remains, however, a lack of consensus on the extent to which the use of higher frequency data will actually im-

[3]See chapter 6, *Evading a Monitoring Network,* for a discussion of treaty constraints.

[4]See chapter 5, *Identifying Seismic Events.*

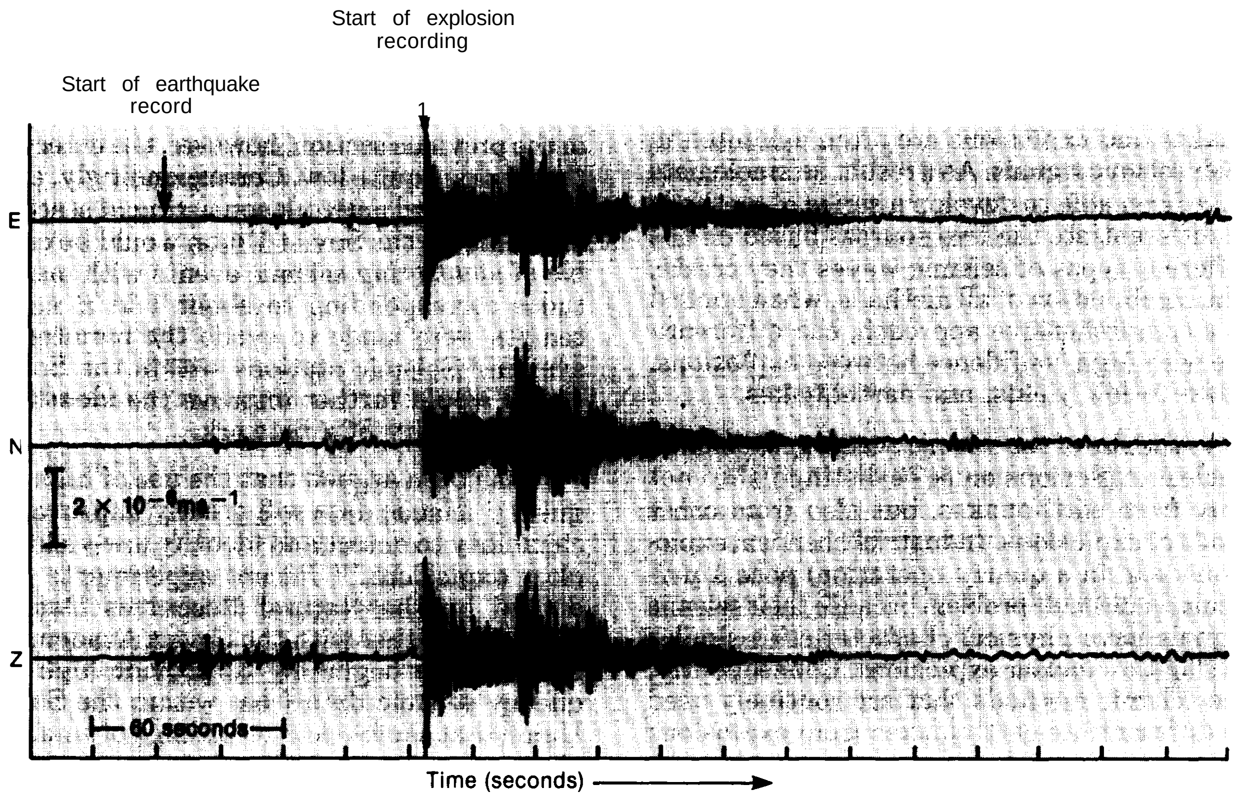
[5]For example, much lower identification thresholds have been defended by J.F. Evernden, C.B. Archarnbeau, and E. Cranswick, "An Evaluation of Seismic Decoupling and Underground Nuclear Test Monitoring Using High-Frequency Seismic Data," *Reviews of Geophysics,* vol. 24, May 1986, pp. 143-215.

[6]See chapter 4, *Detecting Seismic vents,* and chapter 5 *Identifying Seismic Events,* for discussions of high frequency monitoring.

Box 1-A.—NRDC/Soviet Academy of Sciences

New seismic data from the Soviet Union is becoming available through an agreement between the Natural Resources Defense Council and the Soviet Academy of Sciences. The agreement provides for the establishment of a few high-quality seismic stations within the Soviet Union around the area of the Soviet test site in Kazakhstan. The agreement also included experiments in which the Soviet Union detonated chemical explosions of known yield near the test site so that the test site could be calibrated.

The seismograph below is from a 0.01 kt chemical explosion detonated near the Soviet test site and recorded 255 km away. The signal of the explosion can be clearly seen along with the coincidental arrival of seismic waves caused by a large earthquake that occurred south of New Zealand. The three components of ground motion are east-west (E), north-south (N), and vertical (Z).



SOURCE: Natural Resources Defense Council.

prove monitoring capabilities. The lack of consensus is due to differences in opinion as to how well U.S. experience and the limited experience near the Soviet test site can be extrapolated to an actual comprehensive monitoring system throughout the Soviet Union. Consequently, the debate over improved capability will probably remain unresolved until more extensive data can be collected at regional distances from areas throughout the Soviet Union. Nevertheless, there is general agreement among seismologists that good data is obtainable at higher frequencies than those used routinely today, and that this data offers advantages for nuclear monitoring that should continue to be explored.

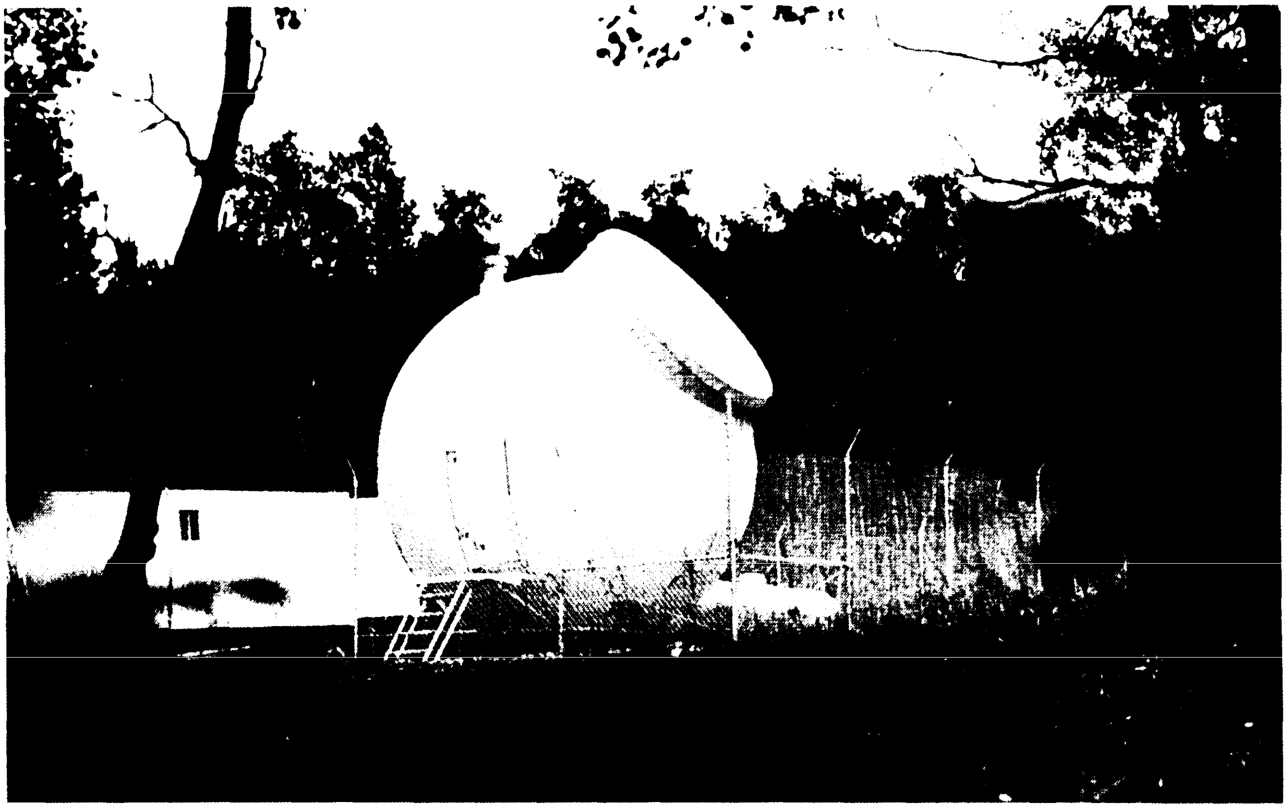


Photo credit: Sand/a National Laboratories

An example of what an internal seismic station might look like.

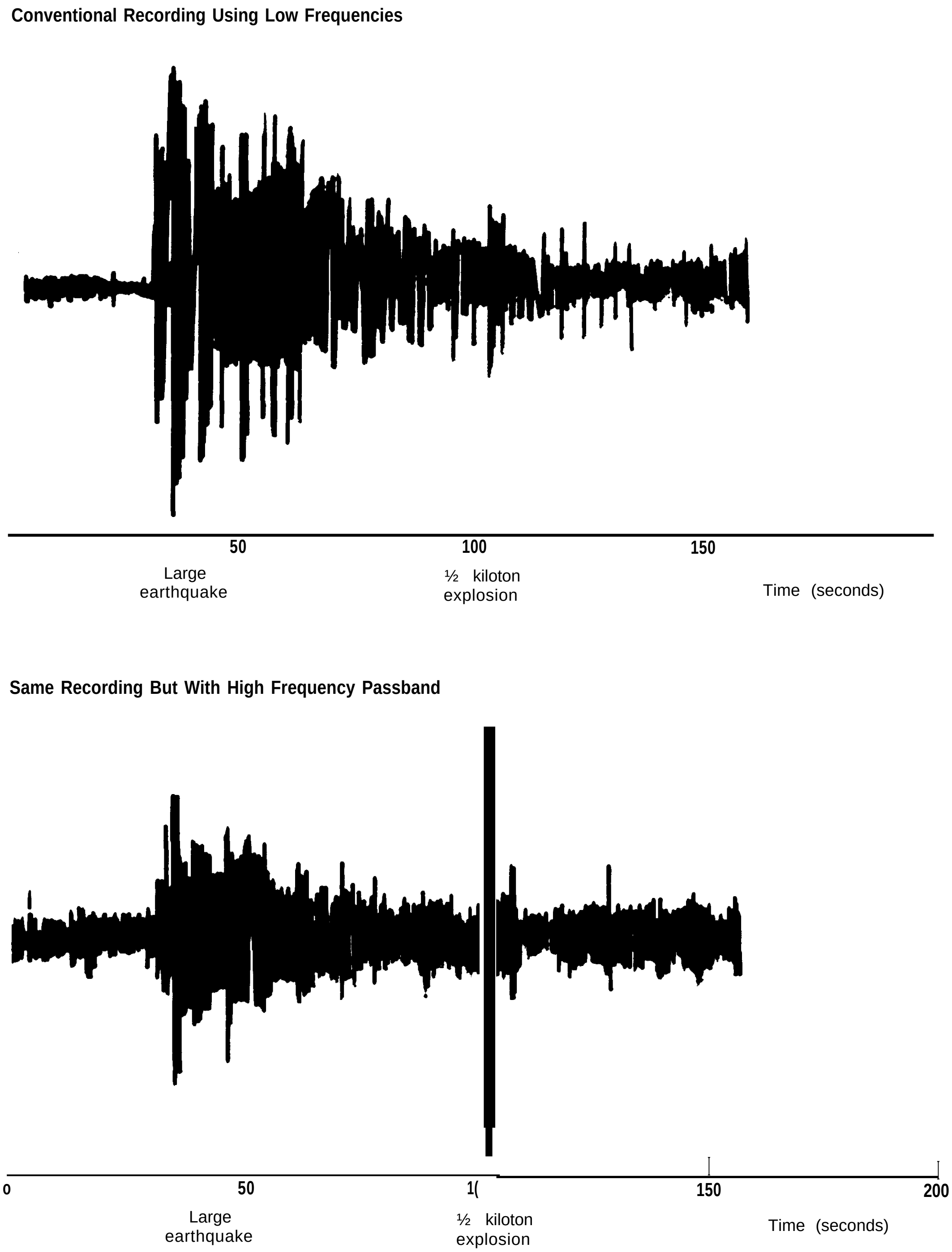
Evading a Seismic Monitoring Network

To monitor a treaty, nuclear tests must be detected and identified with high confidence even if attempts are made to evade the monitoring system. As mentioned earlier, it is the feasibility of various evasion scenarios that sets the lower limit on the monitoring capability. The major evasion concerns are:

- that the signal of an explosion could be hidden in the signal of a naturally occurring earthquake,
- that an explosion could be muffled by detonating it in a large underground cavity, or
- that a nuclear test could be disguised as or masked by a large legitimate industrial explosion.

The hide-in-earthquake scenario assumes that a small nuclear test could be conducted by detonating the explosion during or soon after an earthquake. If the earthquake were sufficiently large and the small explosion properly timed, the seismic signal of the explosion would be hidden in the seismic signal of the earthquake. However, it is not practical for an evader to wait for an earthquake that is in the immediate vicinity of the test site. Therefore, the masking earthquake would have to be large and at some distance. The smaller nuclear explosion will produce higher frequency signals than the earthquake, and filtering the signals will reveal the signals from the explosion (figure 1-2). For this and other reasons (chapter 6), the hide-in-earthquake scenario need no longer be viewed as a credible evasion threat for explosions above 5-10 kt. To counter this threat for explosions below 5-10 kt may require access to data from seismic stations within the Soviet Union, because the higher frequency seismic signals from explosions below 5-10 kt

Figure I-2.—Explosion and Earthquake



Both the upper and lower seismograms were recorded in Norway and cover the same period of time. The upper seismogram is the conventional recording of low-frequency seismic waves. Both it and the lower recording show, at the time of 30 seconds, the arrival of waves from a large earthquake that occurred in the eastern part of the Soviet Union. About one minute after the earthquake, at a time of 100 seconds, the Soviet Union conducted a very small (about ½ kt) underground nuclear explosion at their Kazakhstan test site. With the standard filter (upper seismogram), the signal of the explosion appears hidden by the earthquake. Using a passband filter for higher frequency seismic waves (lower seismogram), the explosion is revealed.

SOURCE: Semiannual Technical Summary for Norwegian Seismic Array for 1984, Royal Norwegian Council for Scientific and Industrial Research, Scientific Report No. 1-84/85.

may not always be picked up by stations outside the Soviet Union.

Decoupling appears to be potentially the most effective of all evasion methods. It involves detonating a nuclear device in a large underground cavity so as to muffle the seismic signal. If the explosion occurs in a large cavity, the explosive stresses are reduced because they are spread over the large area of the cavity wall. At a certain cavity size, the stresses will not exceed the elastic limit of the rock. At such a point, the explosion is said to be "fully decoupled" and the seismic signal be comes greatly reduced. At low seismic frequencies, a fully decoupled explosion may have a signal 70 times smaller than that of a fully coupled explosion. At high frequencies the decoupling factor is probably reduced to somewhere between 10 and 7.

Above 10 kt, decoupling is not considered to be a credible evasion scenario because: 1) the clandestine construction of a cavity large and strong enough to decouple a 10 kt explosion is not feasible; and 2) even if such an explosion were somehow fully decoupled, the seismic signal would stand a good chance of being detected and possibly identified. Therefore, decoupling could be most effective for small explosions up to a few kt, particularly when done in conjunction with a legitimate industrial explosion. For example, a potential evasion method would be to secretly decouple a small nuclear explosion in a large underground cavity and mask or attribute the muffled signals to a large chemical explosion that is simultaneously detonated under the guise of legitimate industrial activity.

As discussed in the section on identification, differentiating a small nuclear explosion from a legitimate industrial explosion associated with mining and quarry blasting is difficult because both produce similar seismic signals. This is not a problem for identification under normal circumstances because industrial explosions in the 1-10 kt range occur less than once a year. However, industrial explosions may create a problem when considering the decoupling evasion scenario. That is, some low-yield decoupled explosions might produce seismic signals comparable to those observed from large chemical explosions and no routine capability has yet been developed to differentiate, with high confidence, between such signals.

None of the evasion scenarios poses any serious problem for monitoring explosions above 10 kt. However, to provide adequate monitoring capability below 10 kt, efforts must be made to limit decoupling opportunities. This would include an internal seismic network and provisions within the treaty (such as pre-notification with the option for on-site inspection) to handle the large numbers of chemical explosions. At a few kt, decoupling becomes possible when considered as part of an evasion sce nario. Arranging such a test, however, would be both difficult and expensive; and it is not clear that the evader could have confidence that such a test (even if it were successful) would go undiscovered. However, the possibility remains that a few tests of small magnitude could be conducted and remain unidentified as nuclear explosions.

HOW LOW CAN WE GO?

Given all the strengths and limitations of seismic methods in detecting and identifying Soviet nuclear explosions, combined with the credibility of the various evasion scenarios, the ultimate question of interest for monitoring any low-yield threshold test ban treaty is essentially: *How low can we go?* The answer to that question depends largely on what is negotiated in the treaty. As we have seen, the challenge for a monitoring network is to demonstrate a capability to distinguish credible evasion attempts from the background of frequent earthquakes and legitimate industrial explosions that occur at low yields.

The monitoring burden placed on the seismic network by various evasion scenarios can be greatly lessened if seismology gets some help. The sources of help are varied and numerous: they include not only seismic monitoring but also other methods such as satellite surveillance, radioactive air sampling, communication intercepts, reports from intelligence agents, information leaks, interviews with defectors and emigres, on-site inspections, etc. The structure of any treaty or agreement should be approached through a combination of seismic methods, treaty constraints, and inspections that will reduce the uncertainties and difficulties of applying seismic monitoring methods to every conceivable test situation. Yet with these considerations in mind, some generalizations can still be made about monitoring at various levels.

Level l–Above 10 kt

Nuclear tests with explosive yields above 10 kt can be readily monitored with high confidence.[7] This can be done with external seismic networks and other national technical means. The seismic signals produced by explosions of this size are discernible and no method of evading a seismic monitoring network is credible. However, for accurate monitoring of a 10 kt threshold treaty it would be desirable to have stations within the Soviet Union for improved yield estimation, plus treaty restrictions for handling the identification of large chemical explosions in areas where decoupling could take place.

Level 2—Below 10 kt but Above **1-2 kt**

Below 10 kt and above 1-2 kt, the monitoring network must demonstrate a capability to defeat evasion scenarios. Constructing an underground cavity of sufficient size to fully decouple an explosion in this range is believed to be feasible in salt, with dedicated effort and resources. Consequently, the signals from explosions below 10 kt could perhaps be muffled. The seismic signals from these small muffled explosions would need not only to be detected, but also distinguished from legitimate chemical industrial explosions and small earthquakes. 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.

Level 3–Below 1-2 kt

For treaty thresholds below 1 or 2 kt, the burden on the monitoring country would be much greater. It would become possible to decouple illegal explosions not only in salt domes but also in media such as granite, alluvium, and layered salt deposits. Although it may prove possible to detect such explosions with an extensive internal network, there is no convincing evidence that such events could be confidently identified with current technology. That is, additional work in identification capability will be required before it can be determined whether such small decoupled explosions could be reliably differentiated from the background of many small earthquakes and routine chemical explosions of comparable magnitude.

Level 4—Comprehensive Test Ban

There will always be some threshold below which seismic monitoring cannot be accom-

[7]The United States and the Soviet Union presently restrict their testing to explosions with yields no greater than 150 **kt**. The bomb dropped on Hiroshima was estimated to have a yield of 13 **kt**.

plished with high certainty. A comprehensive test ban treaty could, however, still be considered adequately verifiable if it were determined that the advantages of such a treaty would outweigh the significance of any undetected clandestine testing (should it occur) below the monitoring threshold.

ESTIMATING THE YIELD OF NUCLEAR EXPLOSIONS

For treaties that limit the testing of nuclear weapons below a specific threshold, the monitoring network not only must detect and identify a seismic event such as a nuclear explosion but also must measure the yield to determine whether it is below the threshold permitted by the treaty. This is presently of great interest with regard to our ability to verify compliance with the 150-kt limit of the 1974 Threshold Test Ban Treaty.

The yield of a nuclear explosion maybe estimated from the seismic signal it produces. Yield estimation is accomplished by measuring from the seismogram the size of an identified seismic wave. When corrected for distance and local effects at the recording station, this measurement is referred to as the seismic magnitude. The relationship between seismic magnitude and explosive yield has been determined using explosions of known yields. This relationship is applied to estimate the size of unknown explosions. The problem is that the relationship was originally determined from U.S. and French testing and calibrated for the Nevada test site. As a result, Soviet tests are measured as if they had been conducted at the Nevada test site unless a correction is made. No correction would be needed if the U.S. and Soviet test sites were geologically identical, but they are not.

The Nevada test site, in the western United States, is in a geologically young and active area that is being deformed by the motion between the North American and Pacific tectonic plates. This recent geologic activity has created an area of anomalously hot and possibly even partially molten rock beneath the Nevada test site. As a result, when an explosion occurs at the Nevada test site, the rock deep beneath Nevada absorbs a large proportion of the seismic energy. The Soviet test site, on the other hand, is more similar to the geology found in the eastern United States. It is a geologically old and stable area, away from any recent plate tectonic activity. When an explosion occurs at the Soviet test site, the cold, solid rock transmits the seismic energy strongly. As a consequence, waves traveling from the main Soviet test site in Eastern Kazakhstan appear much larger than waves traveling from the Nevada test site. Unless that difference is taken into account, the size of Soviet explosions will be greatly overestimated.

The geological difference between the test sites can result in *systematic error,* or *"bias, in* the way that measurements of seismic waves are converted to yield estimates. *Random error* is also introduced into the estimates by the measurement process. Thus, as with any measurement, there is an overall uncertainty associated with determining the size of an underground nuclear explosion. This is true whether the measurement is being made using seismology, hydrodynamic methods, or radiochemical methods. It is a characteristic of the measurement. To represent the uncertainty, measurements are presented by giving the most likely number (the mean value of all measurements) and a range that represents both the random scatter of the measurement and an estimate of the systematic uncertainty in the interpretation of the measurements. It is most likely that the actual value is near the central number and it is increasingly unlikely that the actual number would be found towards either end of the scatter range. When appropriate, the uncertainty range can be expressed by using what is called a "factor of uncertainty. " For example, a factor of 2 uncertainty means that the best estimate of the yield (the "measured central value") when multiplied or divided by 2, defines a range within which the true yield will fall in 95 out of 100 cases. This is the high degree of certainty conventionally used in seismology and may or may not be appropriate in a verification context.[8]

The uncertainty associated with estimates of the systematic error can be greatly reduced by negotiating provisions that restrict testing to specific test sites and by calibrating the test sites. If such calibration were to be an integral part of any future treaty, the concern over systematic errors of this kind would become minimal. The majority of errors that would remain would be random. As discussed in chapter 2, a country considering cheating could not take advantage of the random error, because it would not be possible to predict how the random error would act on any given evasion attempt. In other words, if a country attempted to test above the threshold, it would have to realize that with every test the chances of appearing in compliance would decrease and at the same time the chance that at least one of the tests would appear in unambiguous violation would increase. For this reason, the range of uncertainty should not be considered as a range within which cheating could occur.

Most of the systematic error associated with estimating the yields of Soviet nuclear explosions is due to geological differences between the U.S. and Soviet test sites and in the coupling of the explosion to the Earth. Therefore, the single most important thing that can be done to reduce the uncertainty in yield estimation is to calibrate the test sites. Calibration could be accomplished through an exchange of devices of known yield, or through independent measures of the explosive yield such as can be provided by radiochemical or hydrodynamic methods (See box l-B).

Our present capability to estimate seismically the yields of Soviet explosions is often cited as a factor of two.[9] While this may reflect present operational methods, it is not an accurate representation of our capability. Our capability could be greatly improved by incorporating new methods of yield estimation. Most seismologists feel that if new methods were applied, the resulting uncertainty for measuring explosive yields in the range of 150 kt at the Soviet test site would be closer to a factor of 1.5 than a factor of two.[10] Present methods are stated to be accurate only to a factor of two in part because they have not yet incorporated the newer methods of yield estimation that use surface waves and Lg waves.[11] The uncertainty of this comprehensive approach could be further reduced if calibration shots were performed and testing were restricted to areas of known geologic composition. It is estimated that through such measures, the uncertainty in seismically measuring Soviet tests could be reduced to a level comparable to the uncertainty in seismically measuring U.S. tests. An uncertainty factor of 1.3 is the current capability that seismic methods are able to achieve for estimating yields at the Nevada test site.

As with detection and identification, yield estimation becomes more difficult at low yields. Below about 50 kt, high-quality Lg-wave signals can only be reliably picked up by stations within the Soviet Union less than 2,000 km from the test site. For explosions below 10 kt, the uncertainty increases because small explosions do not always transmit their signals efficiently to the surrounding rock. For small explosions, the uncertainty could be reduced by restricting such tests to depths below the water

[8]See chapter 2, *Seismic Verification in the Context of National Security.*

[9]U. S. Department of State, "Verifying Nuclear Testing Limitations: Possible U.S.-Soviet Cooperation, Special Report No. 152, " Aug. 14, 1986.

[10]This reduction of uncertainly derives from using more than one statistically independent method. Consider as an example the situation where there are three independent methods of calculating the yield of an explosion, all of which (for the sake of this example) have a factor of two uncertainty in a log normal distribution:

# of Methods	Resulting Uncertainty
1	2.0
2	1.6
3	1.5

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

[11]See chapter 7, *Estimating the Yields of Nuclear Explosions.*

table, so that their signal will be transmitted effectively.

Our capability to estimate explosive yields would depend to a large degree on the approach that was taken and what was negotiated in future treaties. If new methods of yield determination were incorporated into the measurements and calibration shots were performed, the capability of seismic methods could be improved to a point comparable to the accuracy of other methods, such as CORRTEX, that require a foreign presence and equipment at the test site. In any case, if the objective of reducing the uncertainty is to reduce the opportunities for cheating, small differences in random uncertainty do not matter.

SOVIET COMPLIANCE

The decision as to what constitutes adequate verification should represent a fair assessment of the perceived dangers of non-compliance. This necessarily involves a weighing of the advantages of the treaty against the feasibility, likelihood, and significance of noncompliance. Such decisions are subjective and in the past have been influenced by the desirability of the treaty and the political attractiveness of particular monitoring systems.[12] Specific concern over compliance with test ban treaties has been heightened by findings by the Reagan Administration that:

> "Soviet nuclear testing activities for a number of tests constitute a likely violation of legal obligations under the Threshold Test Ban Treaty."[13]

Although the 1974 Threshold Test Ban Treaty and the 1976 Peaceful Nuclear Explosions Treaty have remained unratified for over 10 years, both nations have expressed their intent to abide by the yield limit. Because neither the United States nor the Soviet Union has indicated an intention not to ratify the treaties, both parties are obligated under international law (Article 18, the 1969 Vienna Convention on the Law of Treaties) to refrain from acts that would defeat their objective and purpose.

In examining compliance with the 150-kt threshold, seismic evidence is currently considered the most reliable basis for estimating the yields of Soviet underground nuclear explosions.[14] The distribution of Soviet tests indicates that about 10 (out of over 200) Soviet explosions since the signing of the Threshold Test Ban Treaty in 1974 *could* have estimated yields with central values above the 150 kt threshold limit, depending on how the estimate is made.[15] These 10 tests could actually be at or below the 150 kt limit, but have higher yield estimates due to random fluctuations in the seismic signals. In fact, when the same methods of yield estimation are applied to U.S. tests, approximately the same number of U.S. tests also appear to be above the 150 kt threshold limit. These apparent violations, however, do not mean that one, or the other, or both countries have cheated; nor does it mean per se that seismology is an inadequate method of yield estimation. It is inherent in any method of measurement that if several tests are performed at the limit, some of these tests will have estimated central values above the yield limit. Because of the nature 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.

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[12] See chapter 2, *Seismic Verification in the Context of National Security.*

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

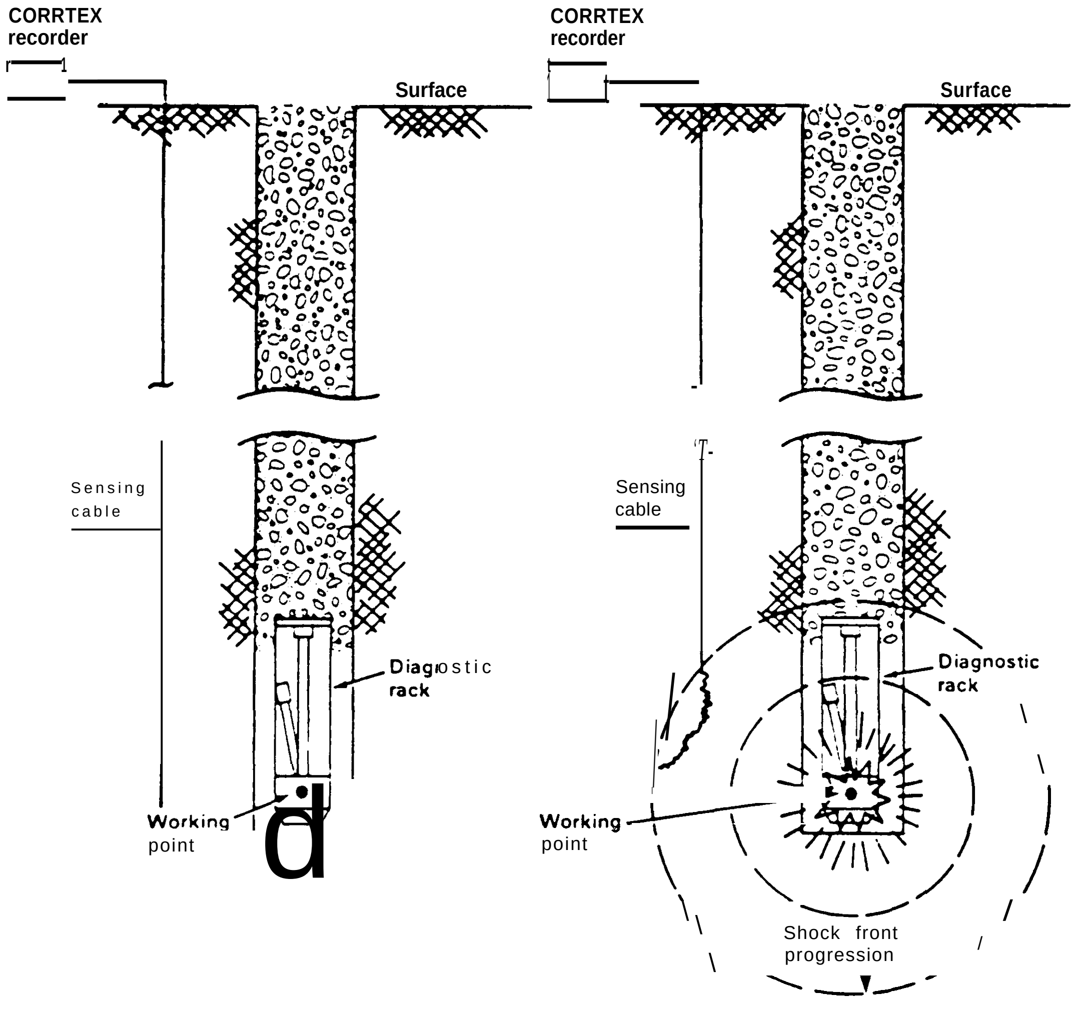
[14] "Conclusion of the Defense Intelligence Agency Review Panel as stated in a letter from Roger E. Batzel, Director of Lawrence Livermore National Laboratory to Senator Claiborne Pen on Feb. 23, 1987.

[15] See chapter 7, *Estimating the Yields of Nuclear Explosions.*

Box 1-B.–CORRTEX

CORRTEX (Continuous Reflectometry for Radius versus Time Experiments) is a technique that was developed in the mid-1970s to improve yield estimation using non-seismic (hydrodynamic) methods. In the CORRTEX technique, a satellite hole is drilled parallel to the emplacement hole of the nuclear device and an electrical sensing cable is lowered down the hole (see figure). When the explosion occurs, a shock wave moves outward crushing and electrically shorting the cable.

By measuring with electronic equipment at the surface the rate at which the cable is shorted out, the rate of expansion of the shock wave can be calculated. From the rate of expansion of the shock wave and the properties of the surrounding medium, the yield of the nuclear device can be estimated. A full assessment of this method is presented in the Appendix, *Hydrodynamic Methods of Yield Estimation.*



Typical cable emplacement in satellite hole

Moving shock wave from nuclear detonation crushes and shortens cable

All of the estimates of Soviet and U.S. 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 consistent with compliance with the 150 kt limit of the Threshold Test Ban Treaty.[16 17]

[16] Ibid.

[17] One of the first groups to carry out such statistical studies was Lawrence Livermore National Laboratory. Their conclusion 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.

VERIFICATION OF THE TTBT AND THE PNET

As noted above, the 1974 Threshold Test Ban Treaty and the 1976 Peaceful Nuclear Explosions Treaty have not been ratified. Most recently, the Senate failed to consent to ratification at least in part because of concerns that the size of Soviet explosions cannot be measured with adequate confidence.[18] As a result, for over 10 years the United States has continued to abide by the treaties, yet refused to ratify them, ostensibly because they cannot be adequately verified. Note that if the treaties were ratified, the protocols would come into force calling for an exchange of data which, if validated, would then improve the verification.[19 20] However, the treaty contains no provisions for an independent verification of the data, most importantly, the yields of the calibration shots. Therefore, many experts question the value of such data, unless the data can be validated.

As a solution to the problem of uncertainty in yield estimation, the administration has recently proposed the use of an on-site measurement system called CORRTEX for all tests above 50 kt. The CORRTEX system is stated to have a factor of 1.3 uncertainty for measuring yields greater than 50 kt at the Soviet test site.[21 22] The drawbacks are that it requires prenotification and cooperation of the host country to the extent that foreign personnel and their equipment must be allowed at the test site for each test. Also, CORRTEX has limited application for monitoring a low-yield treaty and none for detecting clandestine testing, and so it would not improve our ability to monitor low-yield testing thresholds.

Alternatively, advanced seismic methods could be used. The advantage of seismic methods is that a continued presence of foreign personnel at the test site would not be necessary. Additionally, our ability to monitor all Soviet testing (not just testing above 50 kt) would be improved. If the Soviet test site was calibrated and advanced seismic methods were utilized, the uncertainty in seismic yield estimation could be reduced to a level comparable to CORRTEX. In fact, CORRTEX could be used to confirm independently the yields of the calibration shots. The Soviet Union has already agreed to the use of CORRTEX for one or two such explosions at the Soviet test site.[23]

[18] *Threshold Test Ban Treaty and Peaceful Nuclear Explosions Treaty,* Hearings before the Senate Committee on Foreign Relations, Jan. 13 and 15, 1987, S. Hrg. 100-115.

[19] The protocol of the TTBT calls for an exchange of geological data plus two calibration shots from each geophysically distinct testing area.

[20] Monitoring would also be improved by the data that would be obtained from all PNE shots that have occurred in the Soviet Union since 1976.

[21] U. S. Department of State, Bureau of Public Affairs, "U.S. Policy Regarding Limitations on Nuclear Testing, Special Report No. 150, " August 1986.

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

[23] Statement of the Secretary of State of the United States and Minister of Foreign Affairs of the Soviet Union, Dec. 9, 1987.

A PHASED APPROACH

If the policy decision were made that treaties further restricting or eliminating the testing of nuclear weapons are in our national interest, then from a verification viewpoint there is much to be said for a phased approach to this goal. Conceptually, it would begin with a limit that can be monitored with high confidence using current methods, but would establish the verification network for the desired lowest level. The threshold would then be lowered as information, experience, and confidence increase.

For example, the United States and the Soviet Union could begin with a treaty that prohibited testing above 10 kt. This is a level that can currently be well monitored seismically.[24] The verification network negotiated within the treaty, however, would be designed with the goal of monitoring down to the 1-2 kt level. This would include a network of advanced seismic stations throughout the Soviet Union to detect off-site testing plus negotiated provisions to reduce evasion possibilities.[25] Principal among these would be to restrict testing to below the water table and to a specified test site where decoupling opportunities would be limited, to require some special handling (such as pre-notification and on-site inspection) for the detonation of large chemical explosions, and to institute measures to confirm a prohibition on decoupling. To reduce the systematic uncertainty in yield estimation, a series of calibration shots would need to be conducted at each test site using either an independent method such as CORRTEX or the exchange of devices of known yield.

After such a network had been in operation for some time, many of the disagreements concerning hypothetical networks would be resolved. It would be known how well seismic waves travel through the geology of the Soviet Union and what noise levels exist in various areas. Through such a process, experience with large-scale monitoring would be gained and there would be more accurate knowledge of what level of monitoring effort is needed. After this information and experience had been obtained, provisions within the treaty could call for the further reduction of the threshold. At that point, it would be better known down to what level monitoring could be accomplished. If it were determined that a lower threshold could be verified, the testing threshold could be set to the new verifiable limit. By the continuation of periodic reviews, the treaty would always be able to use developments in seismology to maximize the restriction of nuclear testing.

This procedure, however, does not take into account any considerations other than seismic verification. It simply presents the maximum restrictions that could be accomplished from a seismic verification standpoint. Considerations other than seismic verification may result indifferent thresholds being more desirable. Lower thresholds, or even a complete ban on testing, may be chosen if the political advantages are seen to outweigh the risk, and if the significance of minor undetected cheating is seen to be small when all monitoring methods are considered. Higher thresholds may be chosen to permit certain types of testing or to avoid placing a threshold at a boundary where particularly significant tests could occur at yields only slightly above the threshold.

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[24] Some experts believe that decoupling is not feasible above 5 kt and consequently, that a 5 kt threshold could be well monitored with existing methods and facilities; while others would place the threshold somewhere between 5 and 10. However, virtually all experts agree that tests above 10 kt can be well monitored, even assuming the monitored country is intent on cheating.

[25] See chapter G, *Evading a Monitoring Network*.