Chapter 6

Methods of Evading a Monitoring Network

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Chapter 6

Methods of Evading a Monitoring Network

Seismic monitoring when combined with treaty constraints and other monitoring methods must demonstrate a capability to defeat any plausible scenario for evading the monitoring network

INTRODUCTION

The previous chapters have discussed the capability of various networks to detect and identify seismic events. From this discussion it is clear that well-coupled nuclear explosions within the Soviet Union could be detected and identified with high confidence down to yields well-below 1 kiloton using a high-quality seismic network. Yet, in deciding what limits on underground nuclear testing could be verified, further considerations are necessary. A country attempting to conduct a clandestine test would presumably use every practical means to evade the monitoring network by reducing, masking, and disguising the seismic signal created by the explosion. Consequently, detection and identification thresholds cannot be directly translated into monitoring capabilities without considering the various possibilities for evasion.

As we will see in this chapter, certain evasion scenarios could create serious problems for a seismic monitoring system under certain conditions. The need to demonstrate that these evasion scenarios can be defeated (i.e., the explosions in question identified) with high confidence is what limits our monitoring capability. The problem of evasion must be dealt with by a combination of seismic methods, treaty constraints, and other monitoring methods that reduce the difficulties and uncertainties of applying seismic monitoring methods to every conceivable test situation. In short, *seismic* monitoring needs some help and the obvious approach is to require the structuring of any treaty or agreement to create a testing environment that makes it much more likely that a combination of prohibitions, inspections, and seismic methods will provide the desired high levels of verification capability.

EVASION SCHEMES

Over the past three decades, researchers have conceived a number of theoretical scenarios by which a low-threshold test ban treaty might be evaded. These include: testing behind the sun, testing in deep space, detonating a series of explosions to simulate an earthquake, testing during or soon after an earthquake, testing in large underground cavities, testing in nonspherical cavities, testing in low-coupling material such as deposits of dry alluvium, and masking a test with a large, legitimate industrial explosion. While some of these scenarios warrant genuine attention from a monitoring perspective, others can be dismissed because of extreme difficulty of execution or even infeasibility. To determine which are which, standards of credibility need to be applied.

For an evasion scenario to be credible it must be technically feasible and it must create a worthwhile advantage for the country considering cheating. As discussed in chapter 2, a country considering cheating would have to evaluate the risks and costs of being caught against the benefits if not caught. The country concerned about preventing cheating has to guess the other country's values for making such decisions. While a slight probability of detection might be sufficient to deter cheating, a much more stringent standard is usually needed to achieve high confidence that any cheating would be detected. Thus, the degree of confidence needed to satisfy the concerned country is often higher than what is needed in practice to prevent cheating.

Although the majority of proposed evasion scenarios have been shown to be readily defeated by a good seismic monitoring network, a few concepts have evoked serious concern and analysis on the part of seismologists and other scientists. The remainder of this first section protides a brief listing of the various evasion scenarios. The following three sections discuss in detail evasion scenarios involving cavity decoupling and how opportunities for decoupling could be reduced. The final section assesses the extent to which the most threatening evasion scenarios limit our capability to monitor seismically underground nuclear explosions.

Testing Behind the Sun or in Deep Space

It has been suggested that the Soviet Union could cheat on all test limitation treaties simply by testing in deep space or behind the sun. The idea is that one or two space vehicles would go behind the sun or into deep space. A nuclear device would be detonated and an instrument package would record the testing information and at a later time transmit the data back to Earth. Some feel that such a testing scenario is both technically and economically feasible. Others feel that the technical sophistication, risk, and uncertainty of such a test exceeds the utility of any information that could be obtained in such a manner. Such a test would bean unambiguous violation of several treaties, and hence, discovery would be costly to the tester. In any case, if clandestine testing behind the sun or in deep space is demonstrated on technical grounds to be a concern, the risk could addressed, albeit at considerable expense, by deploying satellites to orbit around the sun. Such satellites equipped with detectors for thermal photons could monitor explosions in deep space. Alternatively, the risk could be addressed politically by negotiating an agreement to conduct simple inspections of the rare vehicles that go into deep space.

Simulating an Earthquake

It has been suggested that a series of nuclear explosions could be sequentially detonated over the period of a few seconds to mimic the seismic signal created by a naturally occurring earthquake. The purpose of such a sequential detonation would be to create a P-wave amplitude that would indicate an earthquake when using the M_s:m_b discrhninant.[1] This evasion method has been dismissed, however, because it only works if the P-wave amplitude is measured over just one cycle. If the P-wave amplitude is measured over several cycles, the M_s: m_b discrimin ant will indicate an explosion. Furthermore, the sequence of waves simulated by the explosion will only appear as an earthquake over a particular distance range. Consequently, a well-distributed network that records over a variety of ranges would not be fooled. In addition, such an evasion attempt would create large seismic signals that other discrimin ants might recognize as being created by an explosion.

Testing During an Earthquake

The hide-in-earthquake scenario posits that a small explosive test can be conducted without detection by detonating it shortly after a nearby naturally occurring earthquake. If the earthquake is sufficiently large and the explosion is properly timed, the seismic signal of the explosion will be partially or completely hidden by the larger seismic signal of the earthquake. This evasion method was at one time considered a challenge to seismic monitoring even though the technical difficulties associated with the execution have long been known to be great. For example, seismologists currently have no reliable techniques for the short-term prediction of the time, location, and size of earthquakes, and this limitation is unlikely to be overcome in the near future.

[1]A discussion of M_s:m_b and other **discriminants** is presented in chapter 5, "Identifying Seismic Events."

Recent developments in seismic instrumentation and data handling have further reduced the feasibility of this evasion scenario. New seismic instrumentation is now capable of filtering so as to pass only high-frequency seismic waves. Because nuclear explosions produce higher frequency seismic waves than earthquakes, it is often possible to remove the effects of distant earthquakes and see the waves created by the explosion. For this reason and the difficulty of detonating an explosion at the right location and time, the hide-in-earthquake scenario is no longer considered a credible evasion threat. However, because high-frequency seismic waves may not always be detectable at great distances, it maybe necessary to have seismic stations within the Soviet Union to obviate the hide-in-earthquake scenario at yield limits as small as a few kilotons.

Testing in a Large Underground Cavity—Decoupling

If a nuclear explosion is set off in a sufficiently large underground cavity, it will emit seismic waves that are much smaller than those from the same size explosion detonated in a conventional underground test. This scheme, called *cavity decoupling,* has been experimentally verified at small yields. It is the consensus of geologists that significant opportunities exist within the Soviet Union to construct underground cavities suitable for decoupling low yield explosions. Furthermore, it is the consensus of seismologists that seismic waves can be muffled by this technique. Consequently, the technical capability to conduct clandestine decoupled nuclear tests determines the yield threshold below which treaty verification by seismic means alone is no longer possible with high confidence. The later sections of this chapter discuss cavity decoupling scenarios in detail.

Testing in a Nonspherical Cavity

This evasion scenario suggests that the detonation of an explosion in an nonspherical cavity could be used to focus the resulting seismic waves away from monitoring stations. This evasion scenario has been dismissed for two reasons. First, a nonspherical cavity would have no better and perhaps worse decoupling than a spherical cavity of the same volume.[2] Second, a monitoring network would have seismic stations in many directions, not just one. The presence of such stations would increase the risk of detection by at least one station, possibly at an enhanced level.

Testing in Low-Coupling Materials

As discussed in the previous chapters, the proportion of explosive energy converted into seismic waves depends on the type of rock in which the explosion occurs. Low-coupling materials such as dry porous alluvium have air-filled pore spaces that absorb much of the explosive energy. This has led to the concern that a monitoring network could be evaded by detonating an explosion in low-coupling material.

The opportunities for such evasion are thought to be limited in the Soviet Union because no great thicknesses of dry alluvium are known to exist there. In fact, large areas of the Soviet Union are covered with permafrost that would produce well-coupled seismic signals. Estimates of the maximum thickness of alluvium in the Soviet Union indicate that it would only be sufficient to muffle explosions up to 1 or 2 kt. Even if such an opportunity does exist, alluvium is a risky medium for testing because it is easily disturbed. An explosion in alluvium could create a subsidence crater or other surface expression. Consequently, clandestine testing in low-coupling material is considered feasible only for explosions below 1 or 2 kt.

Masking a Test With a Large Chemical Explosion

As discussed in chapter 5, chemical explosions are used routinely in the mining and construction industries. In monitoring a low-yield or comprehensive test ban treaty, there would be concern that large chemical explosions could

[2] L.A. Glenn and J.A. Rial, "Blast-Wave Effects on Decoupling With Axis-Symmetric Cavities, " *Geophysical Journal of the Royal Astronomical Society,* October 1987, pp. 229-239.

be used to mask the signals from a nuclear test. Unlike an earthquake, such explosions could be timed to coincide with a clandestine nuclear test. If done in combination with cavity decoupling, this evasion scenario would be a challenge to a monitoring network. For example, a nuclear explosion of a few kt could be decoupled in a large underground cavity and the reduced seismic signal either masked with the simultaneous detonation of a very large chemical explosion or attributed to a chemical explosion. The combination of decoupling and masking is discussed further in the detailed sections on decoupling scenarios.

PHYSICS OF CAVITY DECOUPLING

An underground nuclear explosion creates seismic waves with a broad range of frequencies. For purposes of seismic detection and identification of small events, frequencies from roughly 1 Hz to perhaps as high as 30 or 50 Hz may be important.

For the lower end of this frequency range, the amplitude or size of the seismic waves created by an explosion is approximately proportional to the total amount of new cavity volume created by the explosion. A conventional, or tamped, test is detonated in a hole whose initial volume is negligible compared to its post-test volume. Because the initial hole is small, the rock surrounding the explosion is driven beyond its elastic limit by the explosion and flows plastically. This flow results in large displacements of the surrounding rock mass, and therefore leads to a large cavity-volume increase around the explosion, and efficient generation of seismic waves.

If, on the other hand, the explosion occurs in a hole of much greater initial volume, the explosive stresses at the cavity wall will be smaller. This results in less flow of the rock, hence less cavity expansion and reduced coupling to seismic waves. If the initial hole is sufficiently large that the stresses in the surrounding rock never exceed the elastic limit, the seismic couplings minimized. Further increase of the emplacement hole size will not further reduce coupling at low frequencies, and the explosion is said to be *fullly decoupled.*

Cavity construction on a scale required for explosion decoupling is possible in either salt of sufficient thickness or in hard rock such as granite. In either case, the cavity volume required for full decoupling increases in proportion to the explosion yield and decreases as the strength of the rock increases.

EFFICIENCY OF CAVITY DECOUPLING

Limits on Cavity Construction in Salt Deposits

Large cavities suitable for decoupled nuclear testing above 1 kt can be constructed in salt deposits either by detonating a nuclear explosion of several tens of kilotons, or by solution mining. For example, a stable, free-standing cavity was created by the U.S. “Salmon” test, a 5.3 kt explosion in a salt dome.[3] This cavity was sufficiently large to decouple the subsequent 0.38 kt “Sterling” nuclear test, which was detonated in the Salmon explosion cavity.[4] Nuclear explosions create cavity volume approximately in proportion to their yield. Thus, applying the yield ratio given in the Salmon/Sterling experiment, an explosion greater than 14 kt would be required to create a cavity sufficient to fully decouple a 1 kt test; similarly, an explosion greater than 140 kt would be required to create a cavity sufficiently large to

[3]U.S. Department of Energy, Office of Public Affairs, Nevada Operations *Office, **Announced** United States Nuclear Tests, **July** 1945 Through December 1983, NVO-209* **(rev.4),** January 1984.

[4]Ibid.

fully decouple a 10 kt test. Explosive construction of cavities adequate to decouple shots above 1 kt would obviously be impossible to accomplish clandestinely. Past nuclear tests in the Soviet Union have produced many cavities suitable for decoupling, but the location and approximate size of most of these is known; and thus evasion opportunities at these sites could be limited if activity at them is monitored.

Solution mining on the required scale would also be difficult to conceal. For example, with present techniques it would take many months or perhaps even a year of continuous operation at high circulation rates to solution mine a cavity adequate to fully decouple a 5 kt explosion. The technology also requires enormous amounts of water and the disposal of enormous amounts of brine, further hindering concealment. However, given that such an operation would be detected and monitored, it might be difficult to distinguish legitimate and evasion-related activity. Concealment of the site would not be necessary if appropriate activity (mining of salt) exists. Consequently, areas of salt deposits might require treaty provisions dealing with chemical explosions with magnitudes comparable to decoupled nuclear explosions.

Apart from the significant problems of concealment and resource application, there do not appear to be constraints preventing the construction, by solution mining, of cavities large enough to fully decouple explosions up to 10 kt. In fact, the Soviet literature reports solution-mined cavities with volumes up to one million cubic meters. If such a cavity could be constructed with a spherical shape, it would be 60 meters in radius. A spherical cavity with a 60 meter radius would have sufficient volume to decouple an explosion up to 14 kt, based on cube root scaling of the U.S. Salmon/Sterling salt dome decoupling experiment. However, these existing large, solution-mined cavities are not spherical. They are highly elongated, irregular in shape, and filled with brine. These features reduce the size of the explosion that could be decoupled in the cavity. Furthermore, the brine in the cavity supports through its own hydrostatic pressure a considerable portion of the overburden (i.e. the weight of the overlying rocks). If the cavity was empty, the overburden pressure would not be supported and the stability of the cavity would be uncertain.

Both salt domes and bedded salt regions have to be considered as candidate locations for construction of decoupling cavities in salt, although the mining procedure would be more complex in bedded salt deposits. To create a cavity in bedded salt, solution mining of soluble layers would have to be combined with explosive mining of insoluble interbeds.

The creep strength of natural rock salt controls the maximum depth at which a stable cavity can be maintained. Cavity collapse or major changes in cavity shape occur over time scales of a few months when the overburden pressure at cavity depth exceeds the internal pressure in the cavity by more than about 20 MPa (200 times atmospheric pressure). This corresponds to a maximum depth of about 1 km for a stable, empty cavity. A brine-filled or gas-pressurized cavity might be stable to about 2 km depth. If a cavity is made by an explosion or by solution mining, the salt will be weakened. This will be a consideration because for weak salt a larger cavity is needed, than predicted for strong salt, to fully decouple a given explosion.

Limits on Cavity Construction in Hard Rock

No cavities have been constructed in hard rock on the scale of those known in salt. There is agreement among verification experts that decoupling cavities with radii up to about 25 meters, suitable for repeated testing up to about 1 or 2 kt, can probably be constructed with existing technology. Repeated testing could likely be detected well enough to get good locations; and the detection of repeated events at the same location would be suspicious. There appear to be no known technological limitations preventing construction of cavities up to perhaps 45 meters radius, suitable for decoupling explosions up to about 10 kt. However, the long-term stability under repeated explosive loading is questionable.

In constructing a cavity of radius larger than about 25 meters, a very extensive network of long cables would be needed to strengthen and pre-stress a large region of the rock surrounding the cavity. Such construction would require an elaborate network of additional tunnels and shafts in the surrounding rock. The technology is untested on this scale and construction may be severely complicated in many areas by the presence of high compressive stresses in the rock and by joints, fractures, and other rock inhomogeneities that are present in even the most uniform granites.

Concealment of such a massive excavation operation from satellite reconnaissance or other National Technical Means would be extremely difficult, and thus some plausible cover operation would probably be necessary. A potential evader would also have to consider the possible leakage along joints of radioactive products such as bomb-produced noble gases. Finally, the evader would also have to be concerned that explosions might result in the unexpected collapse of the cavity and the formation of a crater on the surface. Such a possibility is not without precedent: in the 1984 "Midas Myth" test in Nevada, 14 people were hurt and one man killed during the unexpected formation of a crater above a tiny collapsed cavern at a depth of 1,400 feet.

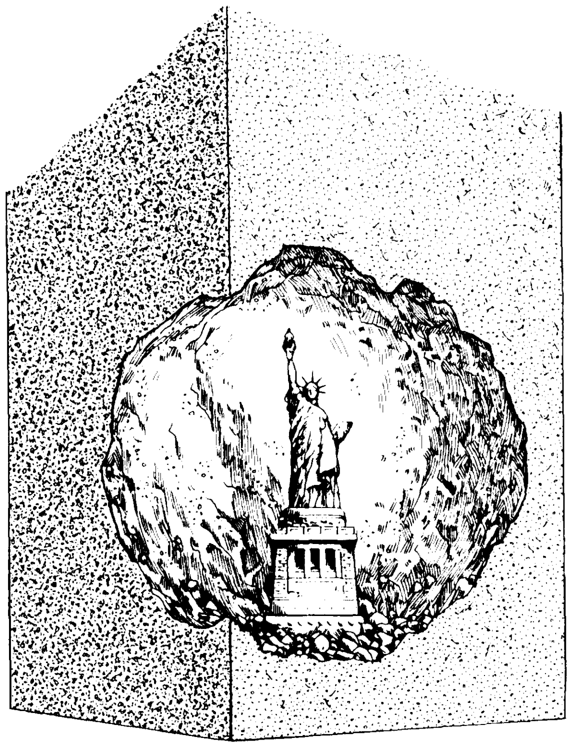
Cavity Size Requirement for Decoupling

The minimum cavity radius required for full decoupling is proportional to the cube root of the explosion yield and inversely proportional to the cube root of the maximum pressure which the overlying rock can sustain without blowing out or collapsing. In salt, the maximum sustainable cavity pressure increases approximately in proportion to depth. Therefore, the minimum cavity size for decoupling is inversely proportional to the cube root of depth (i.e. smaller cavities will work at deeper depths).

As noted above, however, there is a limit to how deep a cavity can be maintained in salt, due to salt's low creep strength. Thus, there are two separate issues regarding the depth of cavities: 1) the deeper the cavity, the smaller the size required to decouple an explosion of a given yield, and 2) the deeper the cavity, the lower the strength of the salt and the more difficult it is to maintain an open cavity. The low strength of salt eventually limits the depth at which a cavity can be created. Even the smallest hole below 1-2 km will squeeze shut.

As discussed earlier, the limiting depth for stability of a large, empty cavity in salt is about 1 km. This depth implies that the Salmon/Sterling cavity (at 0.82 km depth), was very near the maximum depth for stability of an empty cavity. Consequently, the Salmon cavity size approximately sets the lower bound on

Figure 6-1.—Minimum Cavity Size Required To Decouple a 5 kt Nuclear Explosion



To fully decouple a 5 kt explosion in salt, a spherical cavity with a radius of at least 43 meters would be required. The height of the Statue of Liberty with pedestal (240 ft) is 85°/0 of the required diameter (282 ft).

SOURCE: Office of Technology Assessment, 1988 cavity size for full decoupling (at the yield of the Sterling test). This implies a minimum cavity radius of at least 25 meters for full decoupling of a 1 kt test in salt. Cavity requirements are expected to scale as the cube root of the explosion yield. For example, to fully decouple a 5 kt explosion in salt, a spherical cavity with a radius of at least 43 meters (25 times the cube root of 5) would be required (figure 6-l).

In granite, a smaller cavity, perhaps around 20 meters in radius, might be expected to successfully decouple a 1 kt explosion, while a 34 meter cavity would be needed to decouple 5 kt. This number is a rough estimate because it does not take into account the joints and fractures that would be present in even the most uniform granites. The difference between the salt and granite estimates is due to the greater strength of granite, which might therefore sustain a somewhat higher pressure. Such estimates, however, remain uncertain and some experts doubt that the effective strength of granites would be greater than salt and believe that a radius comparable to that of salt would be needed to decouple the same size explosion in granite.

CONSTRAINTS ON DECOUPLING

Decoupling Factors

The reduction of seismic wave amplitudes achievable by full decoupling is called the *decoupling factor*. On theoretical grounds, the decoupling factor is expected to be smaller at high frequencies than at low frequencies.[5] This expectation has been confirmed experimentally. The transition from low-frequency decoupling to high-frequency decoupling occurs over a range of frequencies rather than abruptly, and the transition frequency range depends on yield. For a 1 kt explosion, seismic waves of about 6 Hz and below can be assumed to be controlled by the full low-frequency decoupling factor, whereas seismic waves above 6 Hz will exhibit much less decoupling.

Low Frequencies

Several decoupling experiments have been carried out by the United States. Taken together, these experiments permit us to estimate the low-frequency decoupling factor with considerable confidence. In the 1966 Salmon/Sterling experiment, a smaller nuclear explosion was detonated in the cavity created by a larger explosion. Analysis of the seismic waves from these events led to the conclusion that the low-frequency decoupling factor is approximately 70. That is, a fully decoupled explosion in salt has its low-frequency seismic amplitude reduced by a factor of 70 compared to a "tamped," or "well-coupled," explosion of the same yield in salt. The 1985 Diamond Beech/Mill Yard experiment compared decoupled and tamped nuclear explosions in tuff. In this case, the observed decoupling factor was again 70. The 1959 Cowboy series of tests in dome salt used conventional explosives instead of nuclear explosives. While initial estimates of the decoupling factor from Cowboy ranged from 100 to 150, it was subsequently determined that conventional explosives are significantly less efficient when detonated in a large cavity than when detonated under tamped conditions. When a correction was made for this effect, the Cowboy data yielded an estimate of the full low-frequency decoupling factor of approximately 70, in close agreement with the results obtained in the nuclear experiments.

Earlier theoretical estimates that the low-frequency decoupling factor could be as high as 200 or greater were based on several simplifying assumptions. Seismologists are now in agreement that the experimentally determined decoupling factor of 70 is appropriate at low frequencies.

[5]Donald B. Larson (cd.), Lawrence Livermore National Laboratory, *Proceedings of the Department of Energy Sponsored Cavity Decoupling Workshop, Pajaro Dunes, California*, July 29-31, 1985.

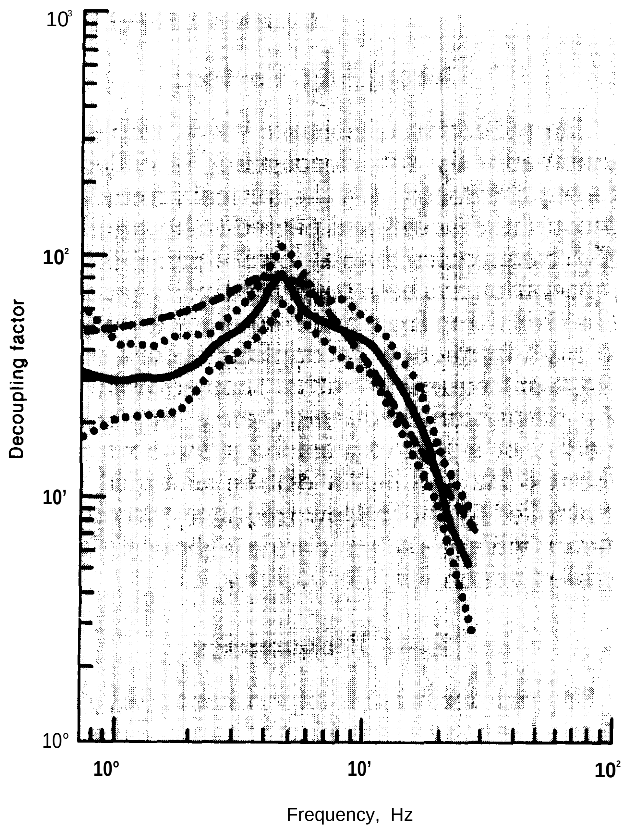
High Frequencies

Roughly speaking, if two explosions excite low-frequency seismic waves whose amplitudes differ by a factor F, their high-frequency seismic waves are expected to have amplitudes whose ratio is approximately the cube root of F. Thus, seismic theory predicts that the decoupling factor will be much reduced at high frequencies. The Salmon/Sterling experimental data corroborate this prediction. Figure 6-2 shows the decoupling factor as a function of frequency inferred from the Salmon/Sterling experiment, with both explosions scaled to 1 kt. As already discussed, the low-frequency decoupling factor averages about 70. However, the experimentally observed decoupling factor begins to drop at about 6 to 8 Hz, and the drop is quite sharp above about 10 Hz. At 20 Hz, the decoupling factor is down to approximately 7. This result can reasonably be extrapolated to estimate decoupling for other yields by scaling the frequency axis in figure 6-2 by the inverse of the cube root of yield. For example, a 5 kt explosion would be expected to be decoupled by a factor of approximately 7 at a frequency of about 12 Hz (20 divided by the cube root of 5). These scaling considerations provide an additional argument in favor of using high-frequency recordings to extend monitoring capabilities down to lower yield levels.

At this time, the exact value of the high-frequency decoupling factor is considered less certain than the low-frequency factor because the instruments recording the Salmon explosion lacked sufficient dynamic range to provide reliable data above 20 Hz. High-frequency data from the Diamond Beech/Mill Yard experiment in tuff also show high-frequency decoupling factors less than 10, consistent with the Salmon/Sterling experience in salt. However, interpretation of the Diamond Beech/Mill Yard data in terms of decoupling is complicated by the facts that the decoupled event was a factor of 100 smaller than the tamped event, the decoupling cavity was hemispherical, the measurements were made at short distances, and the events were not co-located. Data from a better experiment could reduce the uncertainty in the high-frequency decoupling factor.

The evidence for reduced decoupling at high frequencies comes from experiments with spherical (or hemispherical) cavities. However, theoretical calculations show that this conclusion is not altered even when highly elongated

Figure 6-2.—Decoupling Factor as a Function of Frequency



--- Theoretical _ **Average Salmon/Sterling spectral ratio scaled to 1 kt**

•. ••95% Confidence interval

The experimentally observed decoupling factor decreases at higher frequencies.

SOURCE: Modified from J.R. Murphy, Summary of presentation at the ARPA Decoupling Conference, Feb. 7, 1979.

cavity geometry is considered, that is, it does not appear to be possible to increase the high-frequency decoupling factor by constructing specially shaped, air-filled cavities.[6] An evacuated, elongated decoupling cavity may enhance high-frequency decoupling in certain preferred directions, but will decrease high-frequency decoupling in other directions.

[6] Glenn and Rial, op. cit., footnote 2.

DECOUPLING OPPORTUNITIES IN THE SOVIET UNION

Cavity construction for low-yield decoupling is possible in salt domes, bedded salt, and dry hard rock. These geologic categories exclude few areas of the Soviet Union. However, it is generally agreed that salt domes provide the most suitable host rock for large, stable cavities. Salt domes are the most suitable because of the homogeneity of rock salt in domes, the relative simplicity compared to hard rock of constructing stable cavities explosively or by solution mining, and the fact that numerous large cavities already exist in salt domes in the Soviet Union. Cavities confined to a single, homogeneous salt layer in bedded salt, on the other hand, are limited in size by the layer thickness. Assuming that the radius of a cavity in bedded salt should not exceed one-half the layer thickness, decoupling opportunities are probably limited to 1 or 2 kt in bedded salt.

Vast regions of the Soviet Union are underlain by salt deposits. The general distribution of these deposits is indicated by the map in figure 6-3. However, we probably do not know the full extent of Soviet salt deposits. Furthermore, although figure 6-3 indicates those areas where salt domes are prevalent, without access to detailed subsurface geologic data it is not possible to rule out the presence of domes in any area of bedded salt in the Soviet Union.

Because the construction of large salt dome cavities may be difficult to conceal, it is useful to estimate the decoupling opportunity provided by already existing cavities created by Soviet underground explosions (presumed tamped). Table 6-1 summarizes this information. At each yield level, the table shows the number of existing holes large enough for full decoupling. These numbers refer to cavities presumed to have remained open following the largest known Soviet salt dome explosions. The yields in table 6-1 were estimated by dividing the seismically estimated yields of the largest Soviet salt dome explosions by the Salmon/Sterling yield ratio (5.3/0.38 = 14). The use of this ratio is justifiable because the cavity volume created by a tamped explosion (in this case 5.3 kt, Salmon) is proportional to yield and the largest fully decoupled explosion (in this case 0.38 kt, Sterling) is proportional to cavity volume.

Table 6-1 indicates that Soviet decoupling opportunities at 1 kt and above, using existing explosion-generated cavities, are limited to three regions: the North Caspian region, the East Siberian Basin, and a single site in Central Asia. On the basis of table 6-1, there are

Table 6-1.—Numbers of Decoupled Explosions of Yield Greater Than 1 kt That May Be Possible in Cavities Created by Contained U.S.S.R. Underground Explosions, 1961-86[a]

	Yield (kt)				
Areas of known salt deposits	1	2	3	4	5[b]
North Caspian region:					
Azgir	2	4	2	0	
Astrakhan[c]	1	—	—	—	O
Orenburg	2	—	—	—	O
Karachaganak	—	5	—	—	O
Lake Aralsor	—	1	—	—	O
Ishimbay	—	—	—	1	0
East Siberian Basin:					
NW of Lake Baikal	3	2	—	—	O
Within a few x 100 km of basin	1	—	—	1	0
Bukhara, Central Asia (explosion used to extinguish fire in oil well)	—	—	—	1	0

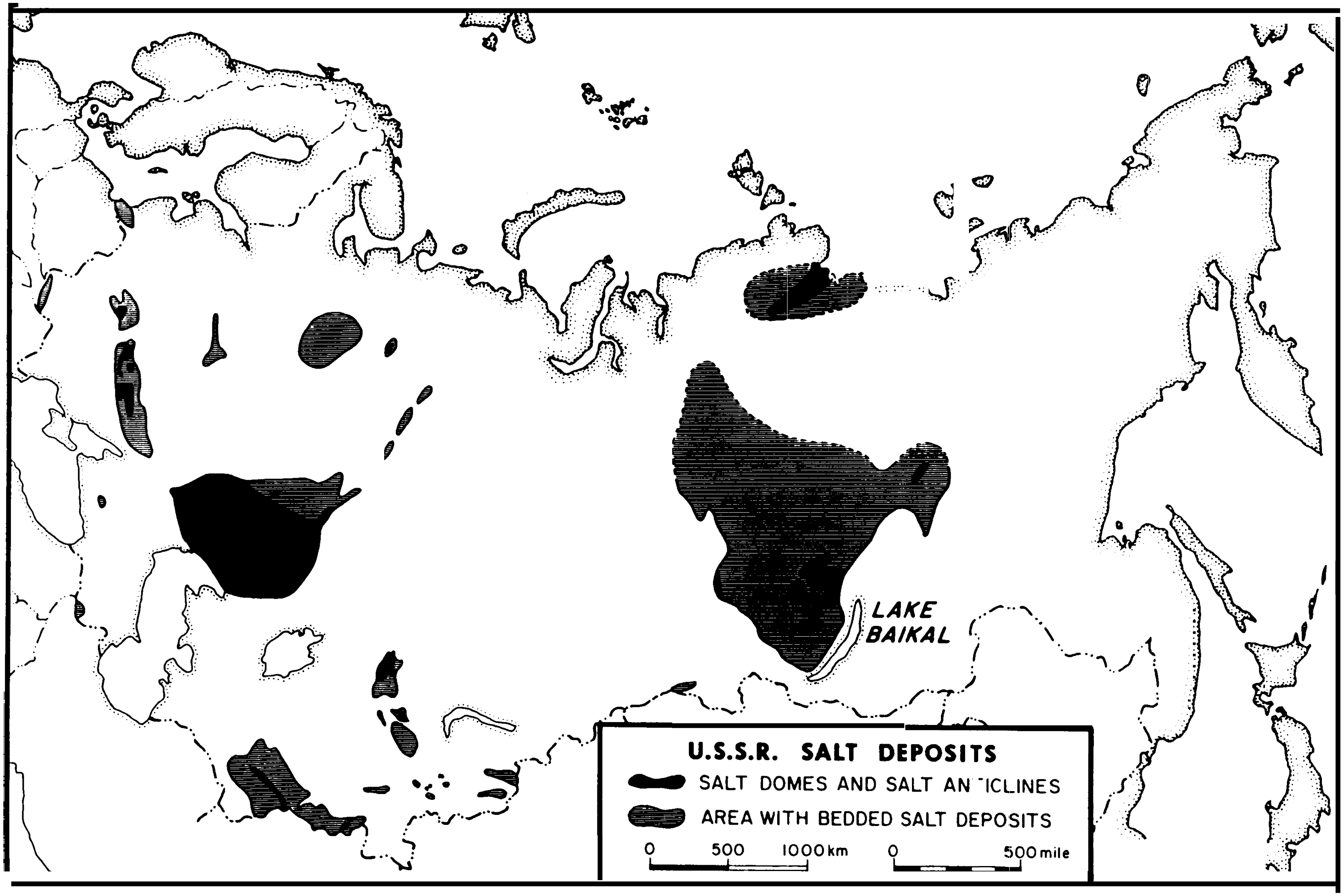
Full decoupling in salt: minimum radius (meters) = 25 • (explosive yield (kt))$^{1/3}$
Full decoupling in hard rock" minimum radius (meters) = 20. (explosive yield (kt))1/3

[a] Obtained from yield of known explosion at site divided by yield ratio for Salmon/Sterling = 5.3/0.38 = 14.

[b] (or greater)

[c] Many cavities capable of being used for full decoupling at yields Of about 05 kt; some could be connected.

Figure 6-3.—Salt Deposits in the Soviet Union



SOURCE: L.R. Sykes, manuscript in preparation.

no opportunities in existing explosion-generated cavities above 4 kt. It should be noted that the potential decoupled yields estimated in table 6-1 depend critically on seismic yield estimates made for the corresponding cavity-generating explosions. The seismic yield estimation procedure used in constructing table 6-1 is one that most seismologists would support, within an uncertainty of about 50 percent. This uncertainty translates into 50 percent uncertainty in the decoupled yields in table 6-1.

PARTIAL DECOUPLING

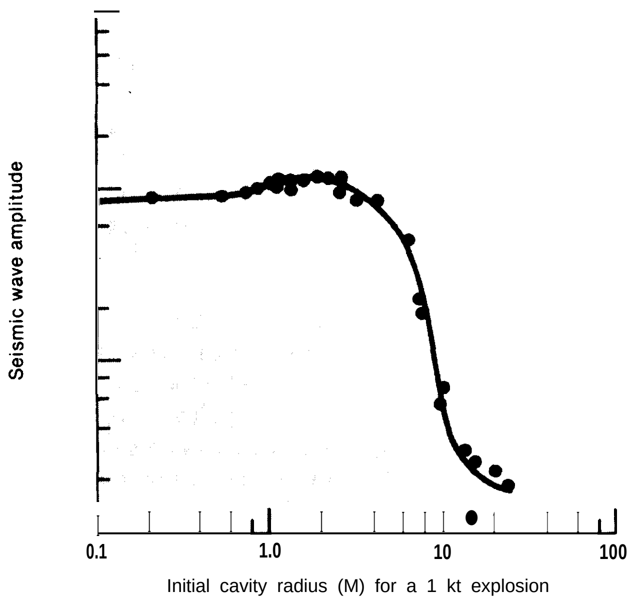
The size of an explosion that could be decoupled is limited by the maximum size of an air-filled cavity that could reasonably be created and remain stable. Concern has been expressed, however, that even if a nuclear device is too large to be fully decoupled, it could perhaps be partially decoupled, thus reducing its seismic signal to some extent. It has been further suggested that by partially decoupling large explosions, a country might be able to clandestinely test above the 150 kt threshold level of the Threshold Test Ban Treaty. As figure 6-4 illustrates, however, partial decoupling is not straightforward.

Figure 6-4 is scaled for the case of a 1 kt explosion and shows how the size of the seismic signal is affected by partial decoupling. As the cavity size first increases, the seismic signal actually gets larger, reaching a maximum for a cavity about 2 meters in radius. The large seismic signal is produced at first in a small cavity because less energy goes into melting rock and more energy is transmitted into seismic waves. For the case of a 1 kt explosion, the radius has to exceed about 4 meters before any reduction of the seismic signal occurs, and must exceed about 6 meters to obtain reduction by more than a factor of 2. After that, further reduction occurs rapidly. If the relationship for a 1 kt explosion is extrapolated to larger explosions, the radius (in meters) of the cavity to begin partial decoupling = 6 * [size of explosion (kt)]1/3. For a 10 kt explosion, the size of the cavity required to begin partial decoupling would be $6 * 10^{1/3} = 13$ meter radius; for 150 kt, the radius would have to exceed 32 meters.

Conducting a partially decoupled explosion also has many risks that the potential evader would have to consider, including the following:

A. Partially decoupling a nuclear explosion is uncertain. As seen in figure 6-4, the reduction in seismic signal occurs along a steep curve. It would be difficult to predict from such a steep curve how much actual decoupling there will be for a given explosion. If partial decoupling is not achieved, an explosion inside a cavity

Figure 6-4.— Partial Decoupling Effect



The effect of partial decoupling scaled for the case of a 1 kt explosion,

SOURCE: Modified from R.W. Terhune, C.M. Snell, and H.C. Rodean, "Enhanced Coupling and Decoupling of Underground Nuclear Explosions," LLNL Report UCRL-52806, Sept. 4, 1979, might actually produce seismic signals larger than a well-coupled explosion.

B Partial decoupling creates greater pressure on the wall of a cavity thi"- full decoupling. For example, a 20 kt explosion set off in a cavity suitable for full decoupling of 10 kt will result in a doubling of the cavity pressure compared to that for the 10 kt shot. Partial decoupling damages the cavity wall and this makes it more difficult to be confident that noble gases and other bomb-produced isotopes will not leak out of the cavity, reach the surface, and be detected. A 20 kt explosion would have to be detonated in a cavity near the maximum possible depth to minimize the pressure on the cavity wall. Risks of deformation or collapse increase with both the yield and the depth of the cavity. A risk trade off would be involved: the desire to minimize the escape of bomb-produced gases leads the evader to construct a cavity as deep as possible, whereas construction difficulties, the time needed for construction, and the risk of cavity deformation or collapse all become increasing problems at greater depths.

MONITORING CAPABILITIES CONSIDERING EVASION

The previous two chapters discussed the various thresholds for the detection and identification of seismic events within the Soviet Union. These thresholds, combined with the feasibility of successfully conducting clandestine decoupled nuclear explosions, effectively determine what levels of nuclear test restrictions can be monitored with high confidence.

As discussed in chapters 4 and 5, well-run seismic monitoring networks can detect and identify underground nuclear explosions with yields well-below 1 kt if no attempt is made to evade the monitoring network. However, a country wanting to test clandestinely above the allowed threshold would presumably attempt to reduce the size of the seismic signal created by the explosion. For example, a country might attempt an evasion scenario where the explosion is secretly decoupled in a large underground cavity and the muffled signals are then masked by or attributed to a large chemical explosion that is simultaneously detonated under the guise of legitimate industrial activity. The problem for the monitoring network is to demonstrate a capability to distinguish such an evasion attempt 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. Countering the various evasion scenarios needs to be approached through a combination of seismic methods, treaty constraints, and other monitoring methods that reduce the difficulties and uncertainties of applying seismic monitoring methods to every conceivable test situation. Specifically, the structure of any treaty or agreement should create a testing environment such that a combination of prohibitions, inspections, and seismic methods will provide the desired high levels of verification capability. Examples of the type of treaty constraints that have been proposed to improve the capability of various monitoring networks include the following:

- **Limitations on Salvo-Fired Chemical Explosions:** All large salvo-fired chemical explosions above a certain size (depending on the threshold being monitored and the area) would be limited and announced well in advance with inspections/monitoring to be conducted on-site by the monitoring side at their discretion.
- Limitations on Ripple-Fired Chemical Explosions: All ripple-fired chemical explosions above a certain size (depending on the threshold being monitored and the area) would be announced in advance with a quota of on-site inspections available to the monitoring party to be used at their discretion.

- **Limitations to One Inspected and Calibrated** Test Site: All tests would be conducted within the boundaries of one defined test area in hard rock or below the water table. Further, several calibration tests recorded by in-country monitoring stations would be allowed with yields spanning the threshold yield. Inspections of the test site would be allowed before enactment of the treaty to ensure that no large cavities suitable for decoupling were present.
- On-going Test Site Inspections: A yearly quota of on-site inspections by the monitoring party would be allowed at the designated test site.
- Joint On-site Inspections of Sites of Possible Violations: A yearly quota of on-site inspections would be allowed at sites designated by the monitoring party with prompt access by a U.S.-Soviet technical team.
- Country-wide Network Calibration Tests: Agreement to conduct a number of large chemical explosions, of both salvo and ripple-fired types, would be allowed to evaluate signal propagation characteristics and detection-identification capabilities in particular critical areas.

If these types of testing constraints can be negotiated within a treaty, reduced thresholds could effectively be monitored. Keeping in mind the various types of networks and negotiated treaty constraints that are possible, the following sections give a sense of the treaty thresholds that could be monitored.

Monitoring Capability Within The U.S.S.R. Using No Internal Stations

The threshold for detecting and locating seismic events within the Soviet Union (90 percent probability of detection at four or more stations), using a seismic network with no internal stations, is at least as low as m_b 3.5 (ch. 4). The associated threshold for the *identification* of 90 percent of all seismic events within the Soviet Union is at least as low as m_b 4.0 (ch. 5). An m_b of 4.0 corresponds to a well-coupled nuclear explosion with a yield of about 1 kt. Consequently, clandestine nuclear explosions above 1 kt would need to be decoupled to evade the monitoring network. Several considerations limit the threshold at which such clandestine nuclear tests might be attempted.

Holes large enough to decouple explosions above a few kilotons would have to be made in salt domes. Almost all of the known salt dome regions of the U.S.S.R. and regions that have any known types and thicknesses of salt deposits are situated in areas of low natural seismicity and good seismic transmission. The detection of seismic events from such areas would probably be better than average.

Even if an explosion were successfully decoupled and the seismic signal muffled down below the 90 percent identification threshold, it might still be identified. Decoupled explosions produce seismic signals that are very *explosion-like.* Because there is no breaking of rock or tectonic release, the signals from decoupled explosions do not look like earthquakes. This makes the identification of a detected event as a decoupled explosion likely. Even though the magnitude of the clandestine test is below the *identification* threshold, the test would in many cases still be well-detected and located. Also, note that the identification threshold is for 90 percent identification, that is, 90 percent of all events above this magnitude will be positively identified. There is no sharp boundary between identification and non-identification. Even if the seismic magnitude from a specific event fell somewhat below the identification threshold, there is a good chance that it would be identified. As discussed earlier, the identification threshold is largely set by the problem of distinguishing large chemical explosions from small decoupled nuclear explosions, so that treaty constraints for handling large chemical explosions would be very helpful.

The largest air-filled cavity that could reasonably be created and remain stable would fully decouple a nuclear explosion of no more than about 10 kt. While large explosions of up to 20 or more kt could theoretically be partially decoupled to produce a seismic signal below the cautious identification threshold, such evasion scenarios are considered implausible because of the practical considerations of containment and predicting the decoupling. In fact, evasion scenarios for explosions above 10 kt are not considered credible by most experts. This means that the monitoring of the Soviet Union with only an external network can be accomplished down to a threshold of about 10 kt. However, for accurate monitoring of a 10 kt treaty, all experts agree that it would be desirable to have stations within the Soviet Union for accurate yield estimation, plus treaty restrictions for handling the identification of large chemical explosions in areas where decoupling could take place.

Monitoring Capabilities Within The U.S.S.R. With Internal Stations

The detection threshold (90 percent probability of detecting a seismic event at four or more stations) is m_b 2.() - 2.5 using a seismic network with internal stations (ch. 4). The associated threshold for the identification of 90 percent of all seismic events is at least as low as m_b 3.5 (ch. 5) and could be reduced depending on what provisions are negotiated to handle chemical explosions. This identification threshold corresponds to a well-coupled nuclear explosion with a yield below 1 kt.

Seismic stations within the Soviet Union would permit lower thresholds to be monitored by reducing the opportunities for evasion. Decoupling is possible for explosions with yields below 10 kt. Consequently, the network of internal stations would be designed primarily to reduce the opportunities for decoupling. The most challenging evasion scenario for such a network would be the situation where a small (1-5 kt) nuclear explosion is decoupled and the reduced seismic signal masked by or attributed to a simultaneous detonation of a legitimate industrial explosion. As noted above, several considerations limit the threshold at which such clandestine nuclear tests might be attempted.

Almost all of the known salt dome regions of the U.S.S.R. and regions that have any known types and thicknesses of salt deposits are situated in areas of low natural seismicity and good seismic transmission. The exceptions include salt deposits in the Caucasus, Tadjikistan, and near the Chinese border. An internal monitoring network should involve the placement of more seismic stations at closer spacing in those few areas. In addition, those areas are all near the southern border of the U.S.S.R. where the detection and identification thresholds either are currently better or can be made better than the average identification threshold by monitoring from nearby countries (i.e., Turkey for Caucasus) and stations inside the U.S.S.R.

Many seismologists feel that the discrimination threshold of m_b 3.5 is too cautious a prediction for the capability of an internal seismic network. This identification threshold is mostly set by the large numbers of chemical explosions that occur below this level. The limitations imposed by identifying chemical explosions can be approached in two ways: first, limiting them by treaty (limiting their size and requiring on-site observers and monitoring) and second, by further developing techniques to make use of the expected differences between the signals created by distributed ripple-fired chemical explosions and the concentrated point explosions characterizing decoupled nuclear tests. While chemical explosions in the U.S.S.R. of m_b 3.0 are likely to be more common than those of m_b 3.5, the monitoring need only be concerned with those chemical explosions of m_b 3.0 and larger that are located in areas of known or possible salt domes. This excludes very large areas of the Soviet Union. A monitoring network with stations internal to the Soviet Union should concentrate on areas of poor transmission and areas where decoupling opportunities would be possible. Through such a strategy and with constraints on chemical explosions, many predict that the identification threshold will be closer to m_b 3.0. This would significantly reduce the size of decoupled explosions that could be clandestinely attempted.

All of the considerations so far have not made allowances for increased verification capability afforded by high-frequency recording. The recent N.R.D.C. recordings to very high frequencies at distances of 200-650 km from three chemical explosions with yields of 0.01 -0.02 kt are very impressive in this regard. From these data, it appears that explosions with yields comparable to a fully decoupled 2.6 -3.8 kt explosion (corresponding to magnitude m_b 3.0) in areas of good transmission will produce large signals with frequencies of 10-20 Hz. This is also a frequency band in which the decoupling factor will be small.

The decoupling reduction that is assumed for these evasion scenarios is a factor of 70. If the monitoring system has even a modest capability to record frequencies as high as 10 -15 Hz, the effectiveness of the decoupling would be greatly reduced. Figure 6-2 indicates a decoupling factor of 30 for frequencies of 1 -2 Hz and 50 as averaged from 1 to 5 Hz. At high frequencies, the decoupling factor will probably be reduced from 70 to below 10. Smaller decoupling factors will result in a lower (better) threshold for the detection and identification of decoupled explosions of a given yield.

Decoupling combined with masking remains a challenging evasion scenario even with a high-quality internal network. Opportunities for such evasion, however, would be limited by the many practical considerations described above and throughout this report. Attempting evasion by this complicated scenario would entail further risk when viewed in conjunction with all types of intelligence gathering, rather than purely as a problem for seismic discrimination. Detected seismic events in areas of possible decoupling would be suspicious and presumably focus attention. On-site inspections could play an important role as opportunities for cheating could be still further reduced by negotiated agreements requiring prior announcement and possible on-site inspections of large chemical explosions in areas of potential decoupling.

Small differences of opinion concerning monitoring capability will always remain because parts of the debate are comparable to discussions of “half-full” versus “half-empty’ glasses of water. Some will review the complex operation of seismic monitoring and will conclude that a country could cheat if any step in the process is uncertain. The chain is only as good as its weakest link. Others will review the complicated evasion scenarios that have been postulated and conclude that evasion is too difficult and uncertain to be credible. Cautious assumptions about seismic monitoring capability and generous assumptions about the likelihood of successfully conducting clandestine decoupled nuclear explosions can be combined to produce the conclusion that even with an internal network an explosion of up to 10 or 20 kt could be partially decoupled in the largest hole (capable of fully decoupling a 10 kt explosion) to create a seismic signal below the m_b 3.5 identification threshold. On the other hand, generous assumptions about monitoring capabilities and favorable assumptions about uncertainty and the role of other intelligence gathering systems can be combined to produce the conclusion that even explosions of a fraction of a kiloton fully decoupled can be effectively monitored with high confidence. Considering all of the arguments, however, a few general statements can still be made concerning monitoring capability with an internal seismic network.

Most experts agree that a high-quality network of internal stations combined with stringent treaty constraints, could monitor a threshold of around 5 kt. Differences of opinion range from 1 to 10 kt and are due to judgments about the level of constraints that can be negotiated into the treaty and what levels of motivation and risk the Soviet Union would be willing to take to test clandestinely slightly above the threshold. Experts further agree that below 1-2 kt, monitoring would become much more difficult because additional methods of evasion are possible. Explosions of 1 or 2 kt could be decoupled not only in salt but also in other media such as granite and alluvium. At present, there is not a consensus that an internal network would be capable of positively identifying with high confidence all such evasion attempts. If such a capability is possible, it will require demonstration through practical experience of low-yield monitoring within the Soviet Union together with a high level of negotiated supplementary measures to limit certain evasion opportunities.