At present, nuclear explosions are limited by treaty to underground testing with yields of no more than 150 kilotons, and recently there have been renewed calls for further test restrictions. As part of these discussions, the U.S. Congress is considering bills that would legislate new limits to testing, whereas the Reagan Administration opposes such constraints. The editors of Science *have asked two groups of participants in the debate to present their arguments for or against new limits to testing. Feiveson, Paine, and von Hippel argue for a treaty of indefinite duration between the United States and the Soviet Union, which includes the following provisions: (i) a ban on all testing outside a designated site having known seismic properties; (ii) verification by means of on-site inspection and in-country seismic monitoring; (iii) unlimited testing below 1 kiloton at the special site; and (iv) an average of one test per year with a yield of up to 15 kilotons for ensuring reliability of the nuclear stockpile. Miller, Brown, and Nordyke argue that a lowering of the present 150-kiloton threshold would be undesirable, and that new test bans would divert attention from a comprehensive approach to negotiated reductions in the nuclear and conventional arsenals of the United States and the Soviet Union.*

A Low-Threshold Test Ban Is Feasible

HAROLD A. FEIVESON, CHRISTOPHER E. PAINE, FRANK VON HIPPEL

IN FEBRUARY 1987, THE REAGAN ADMINISTRATION RESTATED its position on nuclear testing as follows (*1*): "As long as we depend on nuclear weapons for our security, we must insure that those weapons are safe, secure, reliable and effective. This demands some level of underground nuclear testing as permitted by existing treaties." This policy statement does not, however, indicate the frequency and yields of tests that the above objectives would require.

It is our contention that acceptable standards of weapon safety, security, and reliability for the nuclear arsenal could be maintained under a low-threshold test ban treaty (LTTBT) that prohibited all tests except those below 1 kiloton (kt) plus a small number of tests in the 5- to 15-kt range. This position is shared by a number of former high-level weapons designers (*2*).

In this article, we discuss the verifiability of a 1-kt threshold test ban with a quota of above-threshold tests and the impact of such a ban on tests for weapons safety and security, reliability, and weapons effects. We then discuss the opposing positions on the development of more "militarily-effective" nuclear weapons—the principal real issue dividing test-ban advocates and opponents.

Verification. Under a LTTBT, each country would be permitted to test only within the confines of a single designated area. The detection of a nuclear explosion of any magnitude elsewhere would therefore be prima facie evidence of a violation.

There is now general agreement within the expert community that existing external networks of high-performance teleseismic stations have the capability to detect and identify ordinary under-

(Feiveson, continued on page 456)

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Facing Nuclear Reality

GEORGE H. MILLER, PAUL S. BROWN, MILO D. NORDYKE

IT IS A TEMPTING BUT DANGEROUS OVERSIMPLIFICATION OF the complexities surrounding U.S.–Soviet relations to think that abolishing nuclear weapons will eliminate the tensions between our two countries. It is naïve to hope to escape the difficult issues posed by nuclear weapons simply by prohibiting nuclear tests. Proposed new constraints on nuclear testing involve a combination of risks and benefits that must be evaluated in the context of overall U.S. policy. Before we can evaluate these risks and benefits, we must clearly understand the technical issues involved.

The present U.S. nuclear policy is one of deterrence, and under it the capabilities of nuclear weapons and the ongoing nuclear test program are basic to the security of this nation. However, there is a range of ideas as to the nature of "deterrence," from existential deterrence, which asserts that deterrence can be maintained by a few survivable nuclear weapons (*1*), to calculated deterrence, which relies on continued moves and countermoves by the adversaries (*2*). In our view, deterrence is a dynamic condition in which we must respond to technological developments. In the Soviet Union, such developments are mainly nonnuclear and include increased air defense coverage, improved antisubmarine defenses, improved target characteristics (such as hardening), and increasing threats to the survivability of U.S. forces (such as more accurate missiles).

Nuclear weapons testing supports U.S. deterrence in four important ways. First, testing is done to maintain the proper functioning of the current stockpile of weapons. Second, testing is done to enhance the safety, security, and effectiveness of the existing stockpile and to respond to the changing Soviet threat. Third, testing is done to measure the effects of a nuclear attack on our weapons

(Miller, continued on page 460)

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(*Miller, continued from page 455*)

systems and on critical command, control, and communications systems. Finally, testing is done to avoid technological surprise—to identify future weapons concepts for U.S. decision-makers and to stay abreast of potential Soviet nuclear weapons developments.

One must remember that modern nuclear weapons are complex devices. Nuclear weapons produce conditions that are unique on Earth—with material velocities at millions of miles per hour, under temperatures and pressures that are hotter and denser than the center of the sun, and in time scales as short as a few billionths of a second. There is no way to create these extreme conditions in the laboratory.

Nuclear warheads are designed to be enduring and robust. However, there is no such thing as a "thoroughly tested" nuclear weapon. Unlike a sampling program that tests thousands of transistors and unlike the experience gained from the continuous operation of an aircraft, a nuclear weapon typically is fully tested less than ten times during its 20-year lifetime. Any other piece of military hardware undergoes continual testing throughout its lifetime so that deficiencies can be identified and corrected. Nuclear weapons, however, are certified to function properly over a wide range of stressful conditions (temperature, humidity, shock, and so forth) on the basis of a handful of nuclear tests.

Stockpile reliability. The reliability of U.S. nuclear weapons is very high. At issue are the necessary conditions for maintaining high confidence in their reliability. Nuclear weapons are fabricated from chemically and radiologically active materials. Much as a piece of plastic becomes brittle when it is left in the sun, nuclear weapons age and change in subtle, often unpredictable ways. Some of these changes do not adversely affect their performance, but others do. Only by testing can we identify problems and determine if our solutions are successful. We know from experience that testing is essential. One-third of all the weapons placed in the U.S. stockpile since 1958 have required and received post-deployment nuclear tests to resolve problems (*3*). In three-quarters of these cases, the problems were discovered only as a result of nuclear testing.

The provisions of the proposed treaty would be severely restrictive. A 1-kt yield limit would virtually eliminate our ability to maintain confidence in the nuclear stockpile or competence in nuclear technologies. Small-scale nuclear testing—below 1 kt—cannot today be extrapolated reliably by orders of magnitude to provide data on the functioning of a full-scale nuclear device. The fission triggers and their associated technology, which are used in U.S. strategic systems, require nuclear testing at yields greater than 1 kt, and partial-yield testing of the thermonuclear (fusion) component of most of our strategic systems must be done at yields approaching 150 kt. One 15-kt test per year would not be enough to allow us to maintain our technical skills and address all the types of problems that have arisen in the past. Even when a solution could be tested at less than 15 kt, we have frequently needed more than one test to fix a problem, and on occasion a problem with a particular warhead has led to concerns with other warheads.

In addition, we could not maintain scientific competence at this limited level of testing. The fundamental issue here is the quality of our scientific judgement. Nuclear weapons design is still largely an empirical science, and a designer's competence requires years of nuclear test experience. Without actual test experience, nuclear weapons scientists would lack the information needed to solve the various problems that occur with nuclear devices.

The Department of Defense and the Congress are placing more emphasis on reliability testing of radar networks, airplanes, rockets, and other military systems (*4*). Nuclear weapons are more complex than any of these systems, yet the testing to ensure their reliability under all conditions is already severely limited. The proposed treaty would make matters worse. Imagine a test limit on solid rocket boosters, say, that allows partial tests of first stages, only one second-stage test per year, and no test of all three stages. Who could confidently certify the proper functioning of the rocket under these conditions? Such a test program—whether of rocket boosters or nuclear warheads—would result in a loss of reliability and confidence. It would also result in an exodus of experienced people as they left to work on other less restrictive, more productive projects.

Modernization. We believe that the general public often misinterprets the goals of the U.S. modernization program, and sees it as an attempt to perpetuate nuclear weapons. Rather, the primary focus of U.S. modernization is on the enhanced safety, security, and survivability of our nuclear deterrent forces.

As long as the U.S. has nuclear weapons, they must be made as safe and secure as possible. Although there have been no nuclear accidents involving U.S. nuclear weapons, there have been accidents in which the high explosive detonated and dispersed plutonium. Weapons designers have since devised a way to prevent this type of accident. A new insensitive high explosive (IHE) has been developed that is almost impossible to detonate accidentally, and it is being used in new weapons entering the stockpile. Weapons already in the stockpile are being retrofitted with IHE, but it has been incorporated in only one-third of our systems to date. Because IHE performs much differently than previously used explosives, weapons using IHE must be redesigned and retested. Restrictive nuclear test limitations could prevent us from making this and other important changes to the stockpile.

Modern nuclear weapon safety and security features can affect the physics behavior of nuclear devices, and devices incorporating certain features can only be certified to function properly with nuclear tests. A 1-kt yield limit would preclude the incorporation of many safety and security measures. One 15-kt test per year would not provide enough test opportunities to develop new designs using IHE, for example, or to make partial-yield tests of strategic secondaries (the thermonuclear portion of the device) mated to previously tested IHE primaries (the fission portion). Since we could not test the effects of new safety and security features on our nuclear weapons, the weapons would not be modernized with these features.

Even if we use a previously tested warhead in a new system, we need a nuclear test within current yield limits (150 kt) to verify the new production lot. We have found through experience that we cannot specify all the detailed manufacturing criteria that affect weapons performance. Nuclear proof tests are necessary, especially when production runs last for many years and subtle changes can creep into the manufacturing process. Even an identically rebuilt warhead should be verified in a nuclear test to ensure that the slight differences from one production run to another have not affected device performance.

Weapons effects testing. For deterrence to succeed, our forces must not appear vulnerable to the Soviets and thus tempt them to use nuclear weapons in a crisis. We need confidence that our strategic weapons would continue to function even after a nuclear strike. We cannot know this without nuclear testing to determine the effects of nuclear weapons on components of our strategic weapons systems and on the sensors and communications equipment that would have to function after a nuclear detonation. Although aboveground nonnuclear simulators provide useful information, they do not provide a truly realistic test; they cannot, for example, provide for the synergistic effects of the various kinds of nuclear and electromagnetic radiation produced by a nuclear explosion. As in the testing of the weapons themselves, we are often surprised by the effects of nuclear testing on equipment that has performed successfully in nonnuclear tests. Equipment must then be modified and the changes certified in another nuclear test to make sure that these important elements of our deterrent will function properly.

Nuclear-effects tests of U.S. equipment at 1 kt are not adequate today. In principle, effects tests could be performed at low yield if we moved the exposed hardware close to a 1-kt source. However, several problems would have to be solved—for example, damage to delicate hardware (such as a satellite) from ground shock from the explosion. Also, we have not yet demonstrated that it is possible to develop a 1-kt source with a radiation spectrum characteristic of a strategic nuclear weapon.

For economic reasons, we already conduct many of our nuclear-effects tests with yields near or below the proposed 15-kt limit, and we gain much useful information from them. However, we would be severely limited if we could perform only one 15-kt test per year, as specified in the proposed treaty. In addition, there would be many demands for experiments other than weapons effects for that single 15-kt test.

Technological surprise. If our deterrent strategy is to provide stability between the United States and the Soviet Union, we must avoid being surprised by new Soviet technology. We must anticipate changes in the threats we might face and be able to develop new systems in response to new developments. Improvements in nonnuclear features such as guidance, target hardening, and control and communications as well as new nuclear concepts like x-ray lasing have an impact on the effectiveness of our deterrent. We explore new weapons concepts not only with an eye to incorporating them in the U.S. stockpile but also to ensure the survivability of our forces against new Soviet threats. For all the reasons discussed above, these new systems will require nuclear testing.

One area where we are attempting to avoid technological surprise is the concept of a nuclear-driven directed-energy weapon (NDEW). An NDEW uses a nuclear explosive to drive a directed-energy device like a laser. At present, we are attempting to determine the viability of NDEW concepts in the hands of the Soviets to defeat a U.S. nonnuclear strategic defense system or to attack our strategic retaliatory forces in a first strike. Since we do not know how far the Soviet research has progressed, we must determine what is possible and how to defend against it. The proposed treaty would halt virtually all research on NDEW concepts. It would permit some limited research into their basic physics but would preclude the tests that would give us an understanding of their weapons potential.

Whether any NDEW is incorporated as part of a U.S. or Soviet strategic defense system is a political decision. A very important technical question is whether Strategic Defense Initiative (SDI) systems are survivable, and nuclear testing is essential if we are to find the answer. As in nuclear-effects testing of nuclear warheads, SDI assets will have to be tested against realistic nuclear threats. Nuclear testing at current yield levels will be required until we develop the capability to perform the necessary tests at lower yields.

Computer simulations and nonnuclear testing. Critics of nuclear testing have frequently asserted that a viable nuclear deterrent could be maintained with nonnuclear and very low-yield nuclear testing plus computer simulations. A variation of this argument is that although new warheads could not be developed with such testing and computer simulations, they would be adequate for maintaining a stockpile of existing weapons. Neither of these assertions is valid.

The problem lies with the unique nature of nuclear explosives. A nuclear explosion involves myriad physical processes—from the macroscopic down to the microscopic—and they are all interrelated. A nuclear explosion involves most of the physics of a supernova, and the academic community has been working on a computational description of these processes ever since computers were developed. A nuclear explosion also is affected by the microscopic detail of engineering and materials (assembly gaps and grain structure). It simply is not possible with today's computers and computing techniques to include the full range of processes and level of detail in a simulation.

In a computer simulation of a nuclear explosion, we attempt to provide a detailed physical model for all of the interrelated, nonlinear processes that occur. However, computer simulations are inherently limited because (i) the physics must be approximated by numerical algorithms, and these approximations are of varying degrees of accuracy; (ii) not all of the physical processes can be included in detail, given the physical limitations of the computer facilities; and (iii) experimental data are rarely available to confirm the appropriateness of the level of detail in the simulation. In addition, many of the phenomena are interrelated, and so errors from a simulation of early processes will propagate through simulations of subsequent processes. Thus a small error in an early step can grow to yield a calculated result that bears little if any resemblance to the results of an actual test. Usually but not always, our simulations correctly predict general trends in device performance, but sometimes correct detail and important performance parameters can elude us completely.

To minimize potential errors, we normalize our calculations—to the extent that we can—on the basis of the results from actual experiments. Although usually we can recognize that there is an error in a simulation, it is very difficult to identify specifically what is wrong because of the paucity of actual data. The conditions that occur in a nuclear explosion are so unique that we can obtain valid data only from such an explosion, difficult as it is to conduct experiments in so harsh an environment. No experimental facility other than a nuclear explosion itself can give us data about what actually happens in a nuclear explosion. Detailed information accumulates slowly because we do only a limited number of nuclear tests each year.

We make extensive nonnuclear tests on those parts of the system that are amenable to such tests (the high explosive and electrical systems, for example). We then attempt to extrapolate these results to the energy regime of a nuclear explosive (many orders of magnitude greater). Unfortunately, we find that the data from nonnuclear testing, coupled with our most sophisticated calculational procedures, cannot be extrapolated to accurately predict the behavior of a nuclear device.

This problem with extrapolating the results of small-scale tests and computer simulations is not unique to nuclear devices. It is also the case in modern nonnuclear weapons. For example, in modern rockets, small-scale tests and computer simulations do not accurately predict the detailed behavior of solid rocket propellant. Some full-scale tests and actual launches are needed to certify the rocket's proper functioning.

Nuclear tests are particularly important for boosted primaries. Boosting is a process that greatly increases the yield obtained from the fission primary and makes it possible to use much smaller primaries in modern strategic nuclear weapons. However, the boost process is complicated and not fully understood, and some of the stockpile problems encountered to date have arisen from inadequate primary boosting. If boosting of the primary is less than expected, proper ignition of the thermonuclear secondary may not occur and it will fail to produce its designed yield. Hence, to certify the proper functioning of a warhead with a boosted primary, we must be able to certify proper boosting and ignition of the secondary. This requires nuclear testing at yields greater than 1 kt; we cannot today reliably extrapolate the results of a subkiloton test to the performance of a full-scale primary.

A recent example illustrates the essential role of nuclear testing. Just as a new weapon was to be deployed to the stockpile, we made a final proof test at the weapon's specified low-temperature extreme. The test results were a surprise. The primary gave only a small fraction of its expected yield and this was insufficient to drive the secondary. The weapon had been tested extensively in nonnuclear hydrodynamic tests, even at its low-temperature extreme, with no indication of trouble. On the basis of the nonnuclear testing, previous successful nuclear tests, and extensive computer modeling, we had every reason to expect that the low-temperature proof test would produce the predicted yield. However, this low-temperature nuclear test revealed that something was not right. After extensive post-test analysis, we identified the problem and modified the design. Another low-temperature nuclear test was performed and this test was successful, establishing confidence that the warhead would operate properly over its entire temperature range. The production specifications were changed, and the approved, modified warhead entered the stockpile. At present, this stockpile is extremely reliable. But it is reliable only because continued nuclear testing at adequate yields allows us to identify and correct problems as they occur.

The impact of restrictive test limits on the Soviets. We can only surmise the effects of further test limits on the Soviet Union. Since 1963, when the Soviet Union and the United States agreed to conduct nuclear tests only underground, we have learned little about the Soviet nuclear weapons program. What we do know indicates that the Soviets have an aggressive, well-funded program with impressive technical achievements. We know from their unclassified literature that they understand the physics of x-ray lasers. Since nuclear weapons technology is not monolithic, the Soviet designs could be very different from ours. On the basis of the Chernobyl reactor accident, one could infer that they have a different attitude about the enhanced safety and security features that add complexity to U.S. warheads. We also know that the Soviet missiles have a large throw weight. They could use this large throw weight to accommodate warheads that are less technologically sophisticated (and thus larger and heavier) than U.S. designs. The U.S. approach of incorporating sophisticated technologies in its nuclear warheads and in virtually all its military equipment has many important benefits, but it also has attendant costs, including a greater reliance on testing to ensure proper functioning.

We believe that the proposed treaty's limits would be less harmful to the Soviets than to the United States. Given their apparent reliance on larger, less sophisticated and less complex weapons, deterioration of Soviet systems would likely be less of a concern. Restrictive state policies could ensure the retention of their scientific base. Their closed society could allow them to exploit shortcomings in verification of test thresholds at 1 and 15 kt. It would also enable them to secretly prepare for a treaty breakout, as they did before during the nuclear test moratorium of 1958–1961.

Verification of the proposed treaty. Measures to verify compliance with a treaty must enable us to recognize militarily significant clandestine tests with a high degree of certainty. If uncertainties are too high, we have a situation like that with the Threshold Test Ban Treaty (TTBT), where our yield estimates are not sufficiently precise to permit us to make definitive judgements about Soviet compliance with the 150-kt limit. An inability to distinguish reliably between compliance and potential violations can undermine confidence in the arms-control process and can heighten international tensions. Therefore, before we enter into new treaty obligations, we must distinguish between proven verification techniques and possible future capabilities.

The proposed treaty presents a number of verification issues that must be clearly defined and analyzed. Before we can negotitate any treaty involving such a technically complex verification regime, myriad details—many of them not yet apparent—must also be clearly defined. Because of the absence of a comprehensive verification proposal, we will only address the general verification issues raised by the proposed treaty.

A treaty permitting tests with yields up to 1 kt on declared test sites and prohibiting all tests outside those sites would require two separate verification regimes. The first would measure the yields of the permitted tests at the test sites to verify compliance with the 1-kt limit. The second would verify that no clandestine tests were conducted anywhere else in the country; this would be very similar to the regime required to verify a Comprehensive Test Ban Treaty (CTBT). The proposed treaty introduces two other verification requirements—measuring the yield of one test each year with a yield up to 15 kt, and determining that this test consists of only one nuclear device.

Let us first address the country-wide, CTBT-type regime required to preclude clandestine tests outside the test sites. The primary evasion modes are (i) exploding the device in a large underground cavity to decouple the shock wave from the earth and thus reduce its seismic signals; (ii) hiding the seismic signal in the coda (the final portion of the seismic signal) of a large earthquake or chemical explosion; and (iii) conducting the explosion in outer space. It should be made clear that the problem of detecting such evasive tests is greatly complicated by the background of natural or licit events that give rise to false alarms that must be discriminated against.

We would need 25 to 30 high-quality in-country arrays, or equivalent single stations with high signal-to-noise ratios, located inside the Soviet Union to detect signals from kiloton-sized, cavity-decoupled nuclear explosions with high confidence (*5*). Such a network would also greatly improve our ability to detect clandestine nuclear explosions with yields of 5 to 10 kt, or larger, hidden in the coda of a large earthquake.

However, detection does not constitute identification. There are thousands of earthquakes each year in the Soviet Union with magnitudes comparable to decoupled kiloton-scale nuclear explosions. The magnitude level at which we have 90% confidence for identification is presently three to four times greater (in terms of energy) than the magnitude level for detection. Many seismic events are detected that cannot be identified. There are also hundreds of chemical explosions each year that have seismic signals in this same range and thus cannot be discriminated from nuclear explosions. Thus it is obvious that there will be many unidentified seismic events each year that could be decoupled nuclear explosions with militarily significant yields much greater than 1 kt. On-site inspections (OSI) have been suggested as a means for resolving these concerns. However, it is not clear what such OSIs would consist of, how many would be allowed, and what we could expect them realistically to accomplish.

It has been argued that high-frequency seismic signals can be used to significantly improve detection and discrimination of earthquakes from partially or fully decoupled nuclear explosions (*6*). This argument is based on downward extrapolations of results from seismic events that are much larger than those relevant to a CTBT or a 1-kt limit. This argument also makes several assumptions about the high-frequency propagation properties of the upper mantle and crust in the Soviet Union. High-frequency seismic signals may well be useful, but their utility and reliability for detection and identification must be demonstrated in many monitoring environments before we can fully assess their contribution to treaty verification. We are actively working to improve our understanding of these difficult issues.

The testing of nuclear devices in deep space is also a serious concern. Existing rockets could be used to launch a deep-space mission containing a nuclear device and a diagnostics package. All earth-orbiting nuclear-test detection sensors have a detection range that is limited by background noise levels. At a distance well beyond the detection limit of earth-orbiting sensors (determined by the planned yield), the two packages would be separated, the nuclear device fired, and the performance data collected from the diagnostics package and sent back to earth. The time required for such a mission would vary from a month to a year, depending on the yield. It would be much simpler to field than most deep-space probes because the total life of the mission is limited, no external power sources are required, and the experimental measurements are relatively simple, highly automated, and well proven. The only practical way to prevent such tests would be to inspect all space flights large enough for such a mission before launch and to search for highly enriched fissile material.

Proponents of the proposed treaty assert that the ability to conduct one 15-kt test each year would eliminate the motivation to field clandestine tests of this magnitude. However, if one country carried out even two or three more tests each year at 5 to 20 kt than the other country, it would gain a substantial advantage in nuclear weapons technology.

Under a treaty that permits unlimited numbers of 1-kt tests and an average of one 15-kt test per year at designated sites, the primary task would be to verify that the yields are within the allowed limits. Provisions have been suggested to restrict such tests to one test area in hard rock. These provisions attempt to minimize the uncertainties of estimating yields seismically by ensuring that the explosions are well coupled.

However, U.S. experience with estimating the yields of low-yield tests from seismic signals shows that the results are quite variable and easily affected by local geologic structure. Tests in hard, competent rock overlying weak, porous layers can appear to have significantly smaller yields than is actually the case. A country could exploit such a geologic situation to field tests at several times the threshold, thereby gaining a militarily significant advantage. Such problems in unknown or poorly documented geological environments could, in theory, be minimized by requiring all tests to be conducted below the water table. Unfortunately, the United States has virtually no experience with low-yield tests under these conditions.

Calibration explosions, with yields determined by on-site measurements of the speed of the hydrodynamic shock wave, have been suggested (*7*) as a way to reduce the uncertainties associated with seismic coupling and transmission. However, there are many operational and geometrical problems with this technique at low yields and its accuracy has not been established in this yield range.

Another suggestion has been to use multiple seismic phases to reduce the uncertainty associated with seismic yields (*8*). The validity of this approach is being reviewed. This technique, should it prove acceptable for explosions in the 15-kt range and below, would require data from stations inside each country to detect the required regional phases. We would also have to calibrate these stations with a significant number of calibration explosions at the designated test sites.

Because of length limitations, our discussion here is based on many assumptions about provisions of access to each country's territory. The details of such verification provisions are crucial to a verification agreement. Even if such details could be worked out, the shortcomings in our knowledge and capabilities limit our ability to ensure compliance with the provisions of the proposed treaty.

Conclusions. Nuclear weapons that are safe and secure, reliable, survivable, and effective will be a critical element of this nation's deterrent for the foreseeable future. The existence of these weapons reflects the tension that exists between the United States and the Soviet Union. Nuclear test bans will not reduce or eliminate nuclear weapons or this tension. Imprudent nuclear test bans, however, could impair the viability of this vital element of U.S. security.

New, more restrictive test limitations would not enhance our national security. They do not address the two most important issues—namely, major reductions in strategic and conventional forces of both the Soviet Union and the United States, and a widespread lessening of tension between our two countries. In fact, it is conceivable that the diversion of political attention from arms reduction efforts and the distrust generated by test-ban verification problems could actually increase tensions between the two countries.

We believe that more restrictive test limitations or a nuclear test ban should be considered only as part of an integrated and comprehensive approach to arms control. We must reduce the numbers of the most destabilizing weapons and the overall size of the strategic arsenals through negotiations. A restrictive test ban may be a proper last step in our quest for nuclear arms control and a stable peace, but it would, in our opinion, be an imprudent first step. Further test limitations will be consistent with increased stability and decreased tension between the United States and the Soviet Union only if they are instituted after major stabilizing reductions are made in the strategic nuclear and conventional forces of both countries.

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Feiveson, Paine, and von Hippel Respond

We agree with Miller, Brown, and Nordyke on this fundamental point: a low-yield threshold test ban would severely impede the development of new nuclear weapons—including nuclear directed-energy weapons (NDEW) such as the nuclear-pumped x-ray laser under investigation at Livermore Laboratory. We also agree on importance of avoiding technological surprises in the arms race. These are the principal reasons we support a low-threshold test ban.

The suggestion of Miller *et al.* that the Soviet Union might already have NDEWs (an NDEW gap) was originally put forward in 1986 by the Secretary of Energy as a justification for continued U.S. testing during the Soviet unilateral test moratorium. When the CIA was asked to comment, the response was that: "The CIA does not believe that the Soviet Union can deploy nuclear driven directed-energy weapons without conducting additional explosive tests" (*1*).

A low-threshold test ban would impede the development of NDEWs in the Soviet Union at least as effectively as in the United States.

Miller *et al.* disagree with our estimate that an average of less than one allowed test a year with a yield of up to 15 kt would be sufficient to ensure the reliability of the U.S. stockpile. However, they do not offer an alternative quota. If they had, their number would have been close to ours. A listing declassified since we wrote our paper shows that, during the period 1961–1987, there were 39 nuclear explosive tests conducted for the purpose of correcting problems in stockpiled weapons—an average of 1.5 per year (*2*). More relevant to the question of a low-threshold test-ban treaty, however, is the fact that only two to three of these tests were conducted more than 4 years after the weapons entered the stockpile (*3*). In the absence of the introduction of new warheads, therefore, we would expect that the rate of required stockpile confidence tests would quickly drop to a very low level.

With respect to verification, while Miller *et al.* do not dispute the feasibility of detecting even muffled underground 1-kt explosions with a practicable number of in-country seismic stations, they doubt whether seismologists could use the stronger high-frequency content of explosions to distinguish them from earthquakes. However, high-frequency seismology has already demonstrated dramatically that it can deal with one of the principal evasion possibilities cited by Miller *et al.*—hiding a small nuclear explosion in the coda of an earthquake (Fig. 1) (*4*). The problem of distinguishing nuclear from chemical explosions may also be easier at high frequencies because the large chemical explosions used for mining are usually actually "ripples" of small explosions and should therefore have a lower high-frequency content than muffled nuclear explosions with the same signal strength at low frequencies (*5*). Finally, Miller *et al.* are apparently unaware that the Soviet government has already expressed a willingness to accept a remedy suggested to the problem of clandestine testing in outer space: prelaunch inspection of space payloads for weapons (*6*). (For Fig. 1 see p. 456)

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2. See table 2 in *Nuclear Weapons Tests: The Role of the University of California–Department of Energy Laboratories* (University of California, July 1987). Curiously, all of these tests occurred in two periods: 1961–1964 (28 tests) after a 3-year testing moratorium and 1980–1987 (11 tests).
3. For production dates see table 1.2 in T. B. Cochran, W. M. Arkin, R. S. Norris, M. M. Hoenig, *U.S. Nuclear Warhead Production* (Ballinger, Cambridge, MA, 1987).
4. *Semiannual Technical Summary, 1 April–30 September, 1984* [*Norwegian Seismic Array*], L. B. Loughron, Ed. (Report 1-84/85, Kjellor, Norway), p. 62.
5. C. B. Archambeau, private communication.
6. See reference 8 in the contribution to this Policy Forum by H. Feiveson, C. Paine, and F. von Hippel.