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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(*Feiveson, continued on page 455*)

ground nuclear explosions in hard rock down to 1 kt anywhere in the Soviet Union and well below that in some areas (*3*). However, it has been known since 1959 that it is possible to muffle or "decouple" small nuclear explosions in large underground caverns. In a cavity with a radius large enough so that the energy of the shock wave could be absorbed by elastic deformation of the rock, the apparent yield of an underground nuclear explosion could be reduced by a factor of about 100.

Such "full decoupling" of even low-yield explosions would be a difficult and uncertain task. Leakage of radioisotopes would have to be prevented, and the cavity would have to be protected against collapse subsequent to the blast to avoid creating a telltale subsidence crater at the surface. The full decoupling of a 5-kt explosion would require a cavity 60 to 90 m in diameter (big enough to contain a 20- to 30-story building) (*4*). Because the volume of the cavern required increases in direct proportion to the yield of the nuclear explosion, it is generally agreed that full decoupling would be completely impractical for yields above 10 kt.

Nevertheless, since decoupling in the 1- to 10-kt yield range cannot be entirely ruled out as an evasion technique, verification of any treaty banning nuclear explosions with less than 10 kt yield would require internal as well as external seismic monitoring stations. It appears to be generally agreed that, with 25 to 30 carefully sited seismic stations within the Soviet Union, even fully decoupled nuclear explosions could be reliably detected and identified down to yields of a few kilotons. Using the fact that, like small explosions, decoupled ones radiate a much larger fraction of their seismic energy at high frequencies, some seismologists argue that a network equipped with high-frequency (5 to 50 Hz) seismometers could detect and reliably distinguish from earthquakes decoupled nuclear explosions down to approximately 1 kt (*4*).

In regions containing rock suitable for large decoupling caverns, however, arrangements would be needed to verify that large chemical explosions involving tens of tons of explosives were not decoupled low-kiloton nuclear explosions. This would probably require prior notification of major industrial and mining explosions and occasional inspections of the sites of such events.

There would be little pressure to try to carry out clandestine decoupled explosions under the low-threshold treaty being discussed here. The most important benefits that could be derived from these explosions would be legally available through the quota of test explosions of up to 15 kt.

Verification of a low-threshold test ban will also require the capability to estimate the yields of nuclear explosions at the designated test sites to assure that they do not exceed the agreed threshold. For improved verification of the present 150-kt threshold test ban, the Reagan Administration has advocated use of the CORRTEX (Continuous Reflectometry for Radius Versus Time Experiment) method, which would measure the speed of the strong shock wave near the explosion by means of a cable placed in a satellite hole 10 to 15 m from the weapon emplacement hole (*5*). This proposal has caused some concern in the U.S. weapons laboratories because it would be relatively intrusive and require restrictions on the size and contents of the canisters containing the nuclear device and diagnostic equipment (*6*). For a 1-kt threshold, such restrictions would become so stringent and the CORRTEX cable would have to be brought so close to the explosive (2 to 3 m) that the technicians from the two sides would have to work virtually as one team. Seismic yield estimation techniques will therefore be required.

Seismic yield verification for 1- to 10-kt explosions would require in-country seismic stations. The accuracy of the measurements would be improved by requiring that permitted tests be carried out only in strong-coupling (water saturated, for example) media located within the one small designated test area, and by calibrating the seismometers with nuclear explosions of independently determined yield. A modest degree of on-site inspection would be required to verify that the designated test area did not afford opportunities for significant decoupling. Even lacking assurance of compliance with such arrangements, the uncertainty of yield could probably be kept to within a factor of two at one kiloton and 50% at the quota threshold of 15 kt (95% confidence level). Given adequate assurance of compliance with the above arrangements, any extended series of tests exceeding the threshold by 20 to 30% would be detected (*7*). The quota of 5- to 15-kt tests would greatly reduce any incentives to cheat at the margins of the 1-kt threshold.

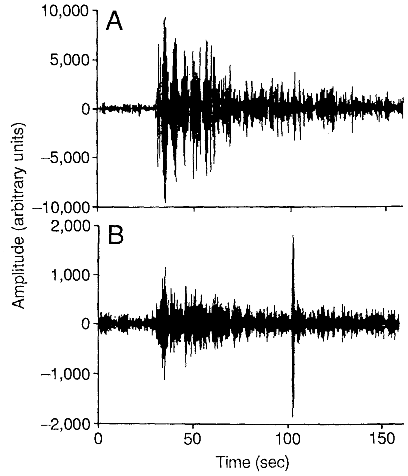

Fig. 1. A comparison of the same events, recorded by the Norwegian Seismic Array in two frequency bands, illustrates the only recently recognized potential for detecting and identifying the signals of small underground explosions by their relatively strong high-frequency content. (**A**) Seismic recording (1.2- to 3.2-Hz band) that shows only the signal from an earthquake in the Soviet Aleutians. (**B**) Seismic recording, taken in the next higher (3.2 to 5.2 Hz) frequency band, in which the amplitude of the signal from the earthquake is reduced by an order of magnitude—revealing (at about 100 seconds) the signal from a 0.5-kt underground explosion at the Soviet Central-Asian test site. (See also pp. 463–464)

The weapons labs and the Department of Energy have recently argued that the Soviet Union might conduct clandestine tests in deep space—behind the sun, for example. We relegate our comments on this scenario to a footnote (*8*).

Safety and security. Another technical reason often given for continued testing is the need to improve the safety of nuclear weapons and their security against unauthorized use.

After four decades of development, the safety design of nuclear weapons is well advanced. In particular, all U.S. nuclear weapons are said to be "one-point safe;" that is, they are designed not to produce a significant nuclear yield even if the chemical explosives are triggered at one point by the penetration of a bullet or by fire. And many U.S. weapons have environmental sensing devices, for example, which sense acceleration and altitude and block triggering signals from reaching the chemical explosives unless the weapon has gone through its intended launch-to-target trajectory. Such systems do not require nuclear testing.

Recent work on safety improvements has been focused on the much less serious problem of reducing the probability of dispersal of toxic plutonium in an accident. An important advance in this regard has been the use since 1980 of "insensitive high explosives" (IHE), which are less susceptible to detonation in abnormal situations such as fires or aircraft crashes. Warheads containing IHE are now available for high-yield and low-yield bombs, all U.S. cruise missiles, the Pershing II, and the MX (*9*). In cases where new warheads containing IHE have not been developed, there is usually no intention to do so for institutional or technical reasons (*10–12*).

Most other improvements do not require certification by a nuclear explosive test. For example, mechanical or electrical design improvements that do not alter the geometry of the fissile material or chemical implosion mechanism in the weapon are ordinarily tested by removing the fissile material and replacing it by non-chain-reacting material such as uranium-238. More sensitive tests of the degree of compression that has been achieved by the chemical implosion are conducted by removing only a part of the fissile material, leaving enough to produce a yield equivalent to a very small nuclear explosion of less than 10^{-6} kt. Measurements of the production of neutrons from such "zero-yield" nuclear tests were, in fact, used by the United States to explore safety problems during the 1958–1961 U.S.–Soviet nuclear testing moratorium (*13*).

Permissive action links (PALs), the electronically coded locks that are used to secure U.S. nuclear weapons from unauthorized use, have already gone through several generations of improvements. The primary issue today is not further technical refinement but rather the fact that many weapons in the U.S. stockpile, including the weapons on ballistic-missile submarines, still have no PALs at all (*14*). A test ban would not prevent the introduction of modern (category D, six-digit code) PALs into currently unprotected weapons or weapons with earlier generation PALs because this type of PAL works on components that do not require nuclear tests to certify their performance (*11*).

Reliability. Concerns raised by the weapons labs that confidence in the reliability of the U.S. nuclear stockpile could not be established in the absence of testing played a key role in derailing President Carter's efforts to achieve a Comprehensive Test Ban (*15*). The technical basis for this concern was immediately challenged in a letter to Carter from a former weapons laboratory director and two former weapon designers (*16*) and the debate has continued among the experts ever since (*17*).

It is difficult for outside observers to reach a conclusion on the technical aspects of the stockpile confidence issue based on such fragments of the debate as have been declassified. However, the public record does support three important findings:

First, as the Department of Energy has acknowledged, weapon designs which are reliable enough to be manufactured without statistically significant numbers of nuclear explosive proof-tests are also reliable enough to be remanufactured in the future (*18*). The issue of warhead reliability therefore concerns the rare case of the appearance of novel design or material flaws that cannot reasonably be remedied by restoring the weapon to original specifications.

Second, because nuclear tests are expensive, only a small number of nuclear explosive tests of stockpiled weapons have been conducted to resolve reliability issues. The principal way in which problems in the stockpile are detected and rectified is by disassembly and inspection, and by nonnuclear tests. During the period 1970–1985 only six to eight underground nuclear explosions were justified by the need to "correct defects in stockpiled weapons" (*19*). A comparable number may have been carried out to determine the seriousness of problems detected during routine disassembly and inspection. The resulting average of about one "stockpile-confidence" test per year should be compared with the average of 16 U.S. nuclear tests per year during this same period (*20*).

Third, to the limited extent that reliability problems have arisen in thermonuclear weapons, apparently virtually all have occurred in their miniaturized fission triggers (*21*).

Judging from the high relative frequency of U.S. tests in the yield range 5 to 15 kt (nearly 40% of all U.S. tests during 1980–1984) (*22*) and our own calculations (*23*), the yields of the triggers for U.S. thermonuclear weapons appear to fall in the range 5 to 15 kt. If future changes in stockpiled thermonuclear weapons were confined to conservative modifications of existing trigger designs, a quota of about one test per year at a yield of about 5 to 15 kt could therefore satisfy the concerns that have been raised about the need for reliability tests. An independent review with full access to the relevant information might well establish that even this small number of tests could be phased out within a few years if no significant changes were introduced into the weapons stockpile.

Nuclear weapons effects. One rationale for continuing underground nuclear explosions that has received increasing public emphasis in recent years has been the need to examine the ability of military equipment—including nuclear warheads and their reentry vehicles—to withstand the effects of nearby nuclear explosions. However, since most of the knowledge obtainable from underground tests can be obtained with explosions with yields of less than 1 kt, the need for "weapons-effects" tests is not a strong argument against an LTTBT. Indeed, for this reason and because tests involving smaller yield explosions are less expensive, most U.S. nuclear weapons effects tests are already conducted at quite low yields (*24*). The permitted quota of higher yield tests could be used for those few applications where a higher energy spectrum of x-rays would be advantageous.

Do we need new types of nuclear weapons? A major benefit to the U.S. of more stringent limits on the testing of nuclear weapons would be to impede the development of new nuclear weapons by the Soviet Union. This benefit is, however, scarcely mentioned by government and laboratory officials involved in the test ban debate. Instead, in their congressional testimony, they reiterate their concern that additional testing restrictions would impede their own work on the development of new nuclear weapons.

For example, in 1985, C. Paul Robinson, then principal associate director for National Security Programs at Los Alamos National Laboratory, argued as follows (*25*): ". . . [a test ban] would prevent us from validating the development of weapons that would allow us to respond to new requirements such as those which may derive from the changes that are occurring in the targets we must hold at risk in the Soviet Union. These requirements might include . . . developing earth penetrating weapons to hold at risk extremely hard, buried targets (missile silos, deep underground facilities) and developing effective means to hold at risk mobile and imprecisely located targets . . . ." Robinson suggested that one way to incapacitate Soviet mobile weapons systems might be with very high levels of microwave radiation generated by a specially designed nuclear weapon. This "third-generation" nuclear weapon concept is now being actively researched at the weapons laboratories—as is the nuclear explosion–pumped x-ray laser for attacking satellites and ballistic missiles in space. Indeed, nuclear directed–energy weapons consume about one half of the U.S. budget for exploratory research on nuclear weapons, and the remaining half is primarily focused on improving U.S. capabilities to attack Soviet nuclear forces (*26*).

Another frequently claimed benefit of continued testing—reduction in the destructiveness of nuclear arsenals—was recently cited in a White House strategy document as follows (*27*): ". . . the United States does not target population as an objective in itself and seeks to minimize collateral damage through more accurate, lower yield weapons." In fact, despite dramatic increases in accuracy, the W-87 warhead for the MX missile has twice the yield of the original warhead on the Minuteman III missile which it is replacing, and the yield of the W-88 warhead for the Trident II missile is about ten times as great as the yield of the warhead on the submarine-launched Poseidon ballistic missile (*28*).

Despite weapons "modernization" to increase the "credibility" of nuclear war fighting postures, the foundation of stable deterrence will continue to be provided by the inescapable mutual vulnerability of the United States and Soviet Union to nuclear attack. Weapons modernization is not only wasteful of resources and scientific talent, however. It is also dangerous. Its justification within both countries demands exaggerated and worst-case caricatures of the adversary's intentions and capabilities and continually reinforces dehumanizing images of the opposing national leadership. Also, the nuclear war-fighting systems that have resulted—for example, the Soviet heavy SS-18 ICBM and the U.S. MX and Trident II—could increase fears of preemptive strikes, undermining restraint in times of crisis.

Effects of a low-threshold test ban. A 1-kt threshold test ban would severely impede the development of all new nuclear missile warheads, bombs, and nuclear directed–energy weapons other than those with yields of a few kilotons or less (*29*). To the extent that a small quota of tests with yields of up to 15 kt were exploited for weapons development rather than reliability and weapons-effects tests, some slow progress might also be made on the development of qualitatively new types of nuclear weapons with yields of tens of kilotons. This is to be contrasted, however, with the current situation of unlimited testing at a yield up to 150 kt—making possible the development of new types of nuclear weapons with yields up to about 500 kt.

However, a low-threshold test ban would not by itself prevent development and deployment of new strategic and tactical nuclear delivery systems. New delivery systems could be developed with nuclear warheads and bombs as a fixed rather than variable parameter in their design. For example, the already tested MX warhead could be mated to the mobile single-warhead Midgetman missile (*30*). Obviously, if optimizing the Midgetman's capability to destroy Soviet strategic nuclear forces and their command facilities is the goal, such a solution may be "sub-optimal" relative to what could be achieved with a new warhead. But, if the purpose of the Midgetman is to improve the survivability of the U.S. strategic nuclear forces, an LTTBT would not be a serious impediment. Indeed, it would forestall developments by the Soviet Union, similar to those underway in the U.S. weapons laboratories (*26*), of nuclear warheads designed specifically for attacks on "strategic relocatable targets" (the Midgetman, for example).

Conclusion. A low-threshold test ban would be an important first step toward redirecting the vast bureaucratic and technical establishments that have been built on the illusion that nuclear weapons can be targeted and employed like other kinds of weapons to achieve traditional military goals. This misguided belief in turn sustains the illusion that endless weapons modernization is the key to national security.

At the same time, an LTTBT with a small quota of 5- to 15-kt tests would meet many, if not all, of the technical concerns raised by the weapons laboratories regarding the reliability, safety, and security of the stockpile and the need to harden critical military systems against weapons effects. It would also allow the weapons laboratories to maintain sufficient expertise to be able to respond to unexpected developments, including the breakdown of the treaty.

The low-threshold test ban would not, unfortunately, provide a guarantee against the development of possibly exotic new types of low-yield weapons and the exploration of the underlying physics and technology that could be used to develop higher yield weapons if the treaty limits were to break down. It would also not have as much direct impact on nonproliferation as would a more comprehensive ban. For these reasons, some arms control experts advocate still more stringent limits. Richard Garwin, for example, would prefer a treaty that would allow (*31*) "explosive releases of nuclear energy taking place only in permanently occupied above-ground buildings. . . ." This might be taken to be a reasonable definition of a comprehensive test ban.

We share the hope that, after in-country seismic monitoring systems are fully established and tested, it will become politically possible to lower the threshold to below 1 kt and eventually to near zero as a result of increased public confidence in nonseismic means of verification. Only then would the nuclear-testing nations be in a position to present the treaty for signature by nonweapons states—thereby obtaining a meaningful technical barrier to the proliferation of thermonucleaar weapons and an additional moral and political barrier to the spread of all nuclear weapons.

REFERENCES AND NOTES

1. *New York Times*, 27 February 1987, p. A3.
2. Letter to Senators Kennedy, Hatfield, and DeConcini signed by H. A. Bethe, N. E. Bradbury, R. L. Garwin, J. C. Mark, G. T. Seaborg, and T. B. Taylor. Harold Brown, a former director of the Livermore National Laboratory and Secretary of Defense during the Carter Administration, although unwilling to align himself with any particular test ban proposal, has stated: "I can support an agreement to limit nuclear tests to a few a year at 10 to 15 kt and all others to 1 to 2 kt" (private communication to C. E. Paine, 5 May 1987).
3. See for example, W. J. Hannon, *Science* 277, 251 (1985).
4. J. F. Evernden, C. B. Archambeau, E. Cranswick, *Rev. Geophys.* **24**, 143 (1986); see p. 149.
5. "Verifying Nuclear Testing Limitations: Possible U.S.–Soviet Cooperation," *Special Report No. 152* (U.S. Department of State, Washington, DC, 1986).
6. See for example, R. E. Batzel, Lawrence Livermore National Laboratory, prepared statement, hearing before the Senate Foreign Relations Committee, 15 January 1987, p. 16.
7. C. B. Archambeau, *Proceedings of the SIPRI/CIPPS Symposium on the Comprehensive Test Ban: Problems and Prospects*, Ottawa, Canada, 23 to 25 October 1986 (Oxford Univ. Press, New York, in press), pp. 4 and 14–15. See also, Archambeau, letter to Senators Kennedy, Hatfield, and DeConcini, 22 April 1987, and private communication.
8. See, for example, the testimony of Livermore Laboratory Director R. E. Batzel, in *Review of Arms Control and Disarmament Activities*, House of Representatives Committee on Armed Services (U.S. Government Printing Office, Washington, DC, 1986), p. 125. Tests in space would have to be done at great range and expense to evade detection by near-earth satellite sensors. If such cheating is truly of concern, the United States could deploy deep-space sensors—or work toward an agreement on nonintrusive prelaunch inspection of space payloads for the presence of nuclear weapons. The Outer Space Treaty forbids the placing of nuclear weapons in space and the Soviet Union has recently expressed a willingness to join in an agreement involving prelaunch inspection for weapons of all types (Ambassador Y. Nazarkine at the Conference on Disarmament, Geneva, 17 March 1987).
9. T. B. Cochran, W. M. Arkin, M. M. Hoenig, *U.S. Nuclear Forces and Capabilities* (Ballinger, Cambridge, MA, 1984), pp. 65, 200, 79, 182, 297, 126, and 133.
10. For example, the Navy has elected not to put IHE in the warhead for its Trident-II ballistic missile because it believes that the safety advantages of IHE are not worth the weight penalty associated with its use. If the Navy changed its mind, the Trident-II could be adapted to use the same warhead as the MX. In the case of artillery shells, their small diameter makes them difficult to convert since a larger volume of IHE is required to release a given amount of energy. Finally, replacement warheads are not being developed for some tactical weapons that are being phased out in favor of precision-guided conventional weapons.
11. See S. Fetter, in *The Comprehensive Nuclear Test Ban: For and Against* (Ballinger, Cambridge, MA, in press).
12. According to the official in charge of DOE's defense programs, "It is DOE policy to incorporate IHE in all warheads under development unless it is determined that use of IHE would cause unacceptable operational penalties for the Department of Defense delivery system, or that its use would simply not be possible for some technical reason. . . .Warheads which do not incorporate IHE are designed to prevent nuclear yield in both normal and abnormal environments and are not considered unsafe. The DOE has not provided, and will never provide, to DOD a warhead which is considered unsafe." See S. Foley, "Responses to questions for DOE budget hearing," Subcommittee on Procurement and Military Nuclear Systems, House Armed Services Committee, 24 February 1987 (U.S. Government Printing Office, Washington, DC, in press).
13. See R. N. Thorn and D. R. Westervelt, *Hydronuclear Experiments* (Report LA-10902-MS, Los Alamos National Laboratory, Los Alamos, NM, 1987).
14. See, for example, T. Julian, in *Preventing Nuclear Terrorism*, P. Leventhal and Y. Alexander, Eds. (Lexington Books, Lexington, MA, 1987), pp. 180–181.
15. J. Carter, *Keeping Faith* (Bantam Books, New York, 1982), p. 229.
16. N. E. Bradbury, R. L. Garwin, J. C. Mark, letter to President Carter, reprinted in *Effects of a Comprehensive Test Ban Treaty on United States National Security Interests*, hearings before the panel on the strategic arms limitation talks and the comprehensive test ban, House Committee on Armed Services (U.S. Government Printing Office, Washington, DC, 1978), p. 181.
17. See, for example, the report by J. W. Rosengren [*Some Little-Publicized Difficulties with a Nuclear Freeze* (Report RDA-TR-122116-001, R&D Associates, Marina Del Ray, CA, 1983)] and the critique of this report by R. E. Kidder [*Evaluation of the 1983 Rosengren Report from the Standpoint of a Comprehensive Test Ban* (Report UCID-20804, Lawrence Livermore National Laboratory, Livermore, CA, 1986)] and subsequent exchanges [J. W. Rosengren, *Stockpile Reliability and Nuclear Test Bans: A Reply to a Critic's Comments* (Report RDA-TR-138522-001, R&D Associates, Arlington, VA, 1986) and R. E. Kidder, *Stockpile Reliability and Nuclear Test Bans: Response to J. W. Rosengren's Defense of His 1983 Report* (Report UCID-20990, Lawrence Livermore National Laboratory, Livermore, CA, 1987)].
18. According to DOE Assistant Secretary for Defense Programs, S. Foley, "New warhead or bomb military characteristics submitted by the Department of Defense for acceptance by the Department of Energy normally contain a requirement that the design, development, and production of the warhead (or bomb) be well documented and involve processes that to the extent possible allow replication of the warhead (or bomb) at a future date. Assuming, therefore, that vendor-supplied

materials and components are still available at the time desired for remanufacture (and this will not necessarily be the case), the remanufacture of existing, well-tested warheads is possible." Department of Energy, *National Security Programs Authorization Act for Fiscal Years 1987 and 1988*, hearings before the House Committee on Armed Services (U.S. Government Printing Office, Washington, DC, 1986), pp. 127–128.
19. Eight tests were cited as necessary in Department of Defense–Arms Control and Disarmament Agency–Department of Energy, joint answer to a question for the record in *Nuclear Testing Issues*, hearing before the Senate Armed Services Committee (U.S. Government Printing Office, Washington, DC, 1986), p. 46. However, on 17 April 1986, in answers provided in writing to questions from Representative E. Markey, S. Foley stated that only six tests were required for this purpose.
20. *World Armaments and Disarmament, SIPRI Yearbook, 1986* (Oxford Univ. Press, New York, 1986), p. 129.
21. D. R. Westervelt, in *Proceedings of the SIPRI/CIPPS Symposium on the Comprehensive Test Ban: Problems and Prospects*, Ottawa, Canada, 23 to 25 October 1986 (Oxford Univ. Press, New York, in press).
22. R. E. Kidder, in *Proceedings of the Department of Energy Sponsored Cavity Decoupling Workshop, Pajaro Dunes, California, 29–31 July 1985* (Report CONF-850779, Department of Energy, Washington, DC), p. V25.
23. F. N. von Hippel, H. A. Feiveson, C. E. Paine, *International Security*, in press.
24. R. S. Norris, T. B. Cochran, W. M. Arkin, *Known U.S. Nuclear Tests, July 1945 to 16 October 1986* [Report 86-2 (rev. 1), Natural Resources Defense Council, Washington, DC, 1986].
25. C. P. Robinson, in *Review of Arms Control and Disarmament Activities*, hearings of the House Armed Services Committee (U.S. Government Printing Office, Washington, DC, 1985), pp. 140–142.
26. The proposed $2.1-billion budget for U.S. nuclear weapons research and development for fiscal year 1988 includes $480 million for nuclear directed–energy weapons (about one-quarter of the total budget), $428 million for other future weapons technology development and testing (including work on "strategic relocatable targets" and "hard target kill"), and $424 million on warhead development engineering, testing, and certification. The remainder of the budget is for Nevada test site preparation, plant and equipment, and inertial fusion research. See also *Congressional Budget Request: Atomic Energy Defense Activities, vol. 1, FY 1988* (U.S. Department of Energy, Washington, DC, 1987) and *Energy and Water Development Appropriations for FY 1988*, hearings before the House Committee on Appropriations (U.S. Government Printing Office, Washington, DC, 1987), part 6, pp. 643, 736.
27. "National Security Strategy of the United States," The White House, January 1987, p. 21.
28. See pp. 116, 121, 137, and 145, in (*9*).
29. J. C. Mark, in *Public Interest Report* (Federation of American Scientists, Washington, DC, December 1986), p. 12.
30. Former weapons designers R. L. Garwin, J. C. Mark, and H. A. Bethe have wryly observed that, "It might need shock-alleviation mounting for a mobile Midgetman subject to nuclear attack, but the demand for a new warhead is analogous to requiring that one redesign an astronaut before launching him or her into space. Careful attention to packaging will do" [*ibid.* (April 1987), p. 11].
31. R. Garwin, in *ibid.* (December 1986), p. 13.

Miller, Brown, and Nordyke Respond

Although we agree with Feiveson *et al.* on a number of points, we differ with them on the need for nuclear testing and the effectiveness of the verification measures they have proposed. Our perspective is the result of our experience and responsibilities in nuclear weapons design in support of U.S. policies, the knowledge we and our co-workers have gained in participating in negotiations with the Soviets, and our efforts in addressing verification issues. This experience leads us to favor a different approach for maintaining a just and stable peace.

In general, we agree that it is possible to define a verification regime for both yield estimation and off-site monitoring of clandestine explosions that, in theory, and under ideal conditions, would provide reasonable confidence in compliance. However, under real conditions with real stochastic observables, we believe that the complexities of the monitoring tasks inherent in this multilevel treaty will give rise to many questions of compliance and to a deterioration in the level of mutual confidence.

Specifically, Feiveson *et al.* refer to the capabilities of a 25- to 30-station, in-country network for detection of small seismic events, but they fail to recognize that detection is not identification. The number of unidentifiable events would be a serious problem under the proposed treaty. Feiveson *et al.* also do not fully address the problems of monitoring the 1-kt threshold. They envisage that this can be done by seismic means using in-country seismic stations. However, these seismic stations would require calibration which, in turn, would require measuring the yields of calibration explosions with on-site means. We do not know today how to make reliable on-site measurements at the 1-kt level that would be free from systematic errors, either by accident or design. Since the host would know the radiochemistry yield and hence the value of this systematic error, it could be used to systematically cheat on the 1-kt threshold.

In summary, a number of factors must be considered when proposing and evaluating nuclear test verification measures: (i) uncertainties in the capability of a monitoring system and the resulting false alarm problem; (ii) variability in emplacement conditions for explosions at real test sites; (iii) the relationship of proposed yield thresholds and the uncertainties of the verification regime to yield levels at which evasion becomes militarily significant; (iv) the acceptability to both parties of the intrusive or restrictive measures needed to limit and validate the testing environment; and (v) the need for continuous political support of a verification regime in the face of varying national values and international relationships. One only has to reflect on the debate over threshold test ban treaty (TTBT) compliance to see the negative effects that these factors can have on confidence building. The effects would be even worse for multiple lower thresholds. By describing the ideal performance of optimistic verification systems as if they were real, Feiveson *et al.* divert the search for treaty formulations and verification systems that will contribute to increase stability in the long term.

We agree with the other authors that it is an "illusion that nuclear weapons can be targeted and employed like other kinds of weapons to achieve military goals. . . ." The role of nuclear weapons is to deter. We differ in the form that deterrence should take. Their view of "stable deterrence" is "the inescapable mutual vulnerability of the United States and Soviet Union to attack." We believe that deterrence is a dynamic condition that must respond to technological developments in order to keep the vulnerability of both sides indeed mutual. They say that weapon modernization increases the credibility of war fighting. We believe that weapon modernization provides options to limit war to the lowest possible level. This in turn enhances the credibility and stability of deterrence. At the same time, modernization allows us to enhance the safety and security of our weapons in time of peace.

Maintaining effective nuclear weapons requires scientific judgement and technical skills that are honed by nuclear test experience. We consider this requirement to be central to all the reasons for continued testing. Our perspective leads us to disagree with Feiveson *et al.*'s assertion that their proposed treaty will "allow the weapons laboratories to maintain sufficient expertise . . . to be able to respond to unexpected developments, including the breakdown of the treaty." We question the ability to maintain any complex technology without vigorous access to a full spectrum of experimental capabilities.

We see the immediate route to increased stability as major reductions in the most destabilizing weapons systems. Restrictive nuclear test limitations will fail to remove a single weapon from the stockpile. Such limitations should follow, rather than precede, arms reductions. We believe that as long as we rely on nuclear weapons for deterrence, then some level of nuclear testing will be necessary. That level may very well be determined by the current arms control and nuclear testing negotiations in Geneva. ■