POLICY FORUM: ARMS CONTROL

Maintaining a Nuclear Deterrent Under the Test Ban Treaty

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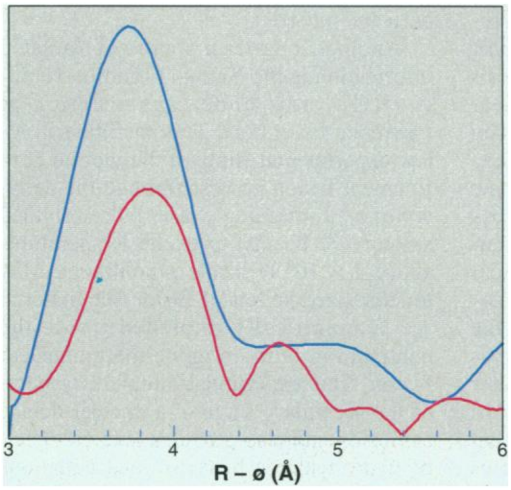
Following the lead of the United States, 152 nations have now signed a Comprehensive Test Ban Treaty (CTBT). This treaty ends all nuclear explosions anywhere and without time limits, after more than 2000 nuclear tests extending over the past 50 years (*1*). It fulfills a commitment made by the nuclear powers in gaining the agreement of 185 nations to indefinitely extend the nuclear Non-Proliferation Treaty (NPT) at its fifth and final scheduled review at the United Nations in 1995. The nations signing the CTBT also agreed to work together to develop stronger and more effective means, both technical and procedural, to verify compliance with the treaty provisions, and this effort is currently under way in Vienna. The CTBT is the cornerstone of the worldwide effort to limit the spread of nuclear weapons and reduce the nuclear danger.

Despite its critical role, the fate of the CTBT hangs in the balance. As called for by Article 14 of the treaty, a review conference will be convened in September or October 1999 to achieve the treaty's early entry into force. The United States will not have a seat at the conference table, however, much less be a world leader in this effort, unless the Senate ratifies the CTBT by that date. Therefore, it is critical that the Senate hold hearings in order to debate the merits of the treaty and bring a ratification decision promptly to a vote. Last spring's nuclear tests by India and Pakistan have added urgency to the importance of ratifying the CTBT before South Asia becomes engulfed in the nuclear weapons spiral. India and Pakistan have announced their intention to adhere to the CTBT by September, but it seems unlikely that they will ratify it if the Senate fails to ratify it.

As a condition of signing the CTBT, the United States had to have confidence, based on sound scientific and technical analysis, that a safe and effective nuclear deterrent can be maintained, consistent with stated national policy, under a total ban on all nuclear tests. The Department of Energy has developed a Stockpile Stewardship Program to meet this requirement. It relies on advanced diagnostic equipment, data from crucial new experiments, greatly enhanced computational power, and the retention of first-class scientists and engineers at the weapon design laboratories (*2*) and production plants (*3*). If well supported and executed, this program will generate a deeper scientifically based understanding of the processes occurring during a nuclear explosion. This will serve as an appropriate replacement for underground nuclear tests, which previously gave the ultimate assurance of the reliable performance of nuclear devices (*4*).



Aged alloy. Synchrotron-based x-ray absorption spectroscopy characterizes the crystal-structural stability of new (blue) and aged (red) plutonium alloy used in weapons. Part of the radial distribution function (histogram of Pu-Pu bond lengths) exhibits the presence of an anomalous peak at 3.8 Å that is not part of the normal crystal structure of delta-plutonium. The decrease in peak amplitude shows that this alloy "improves" with aging, in that the local structure becomes more like that of the stable delta phase (*7*).

Here we describe the basic elements of the program that we believe to be necessary, based on what we know from our extensive involvement in official technical studies (*5*), to provide confidence to government leaders that the United States is meeting its national security requirements in compliance with the CTBT.

Immediate priority must be given to addressing short-term needs affecting the nuclear weapons stockpile over 5 to 10 years. This means implementing a surveillance program to ensure timely detection of any significant effects of aging in nuclear weapons and to identify ways of fixing the weapons as required. In particular, materials science is important for ensuring the reliability of the crucial primary stage of a nuclear weapon. If its yield is too low, the primary stage cannot ignite the secondary stage that provides the bulk of the energy release from a modern thermonuclear weapon, and the weapon fails.

Aging-induced changes that must be understood and monitored include (i) changes in plutonium properties as defects and impurities build up because of radioactive decay; (ii) structural or chemical degradation of high explosives that could lead to a change in performance during implosion of the primary stage; and (iii) physical degradation of materials or components, such as corrosion along interfaces, joints, and welds.

Alpha decay of ^{239}Pu ($^{239}Pu \rightarrow$ $^{235}U + {}^{4}He$) causes the displacement of each atom once per decade, on average, inevitably changing the primary assembly over time. The deterioration can include microscopic disordering of the metal; migration of helium and other impurities to and from grain boundaries; formation of helium bubbles; local conversion of plutonium from the delta to the alpha phase; and macroscopic swelling, shrinking, or creep of the metal. These symptoms can change the equation of state, elastic moduli, and conditions of melting of the bulk metal. Because of its long half-life (24,100 years), it would take a long time to experimentally document the effects of decay-induced aging in ^{239}Pu. Fortunately, one can accelerate the aging process by mixing in ^{238}Pu, which undergoes alpha decay and hence radiation-induced aging at a rate 275 times faster (that is, 14 times faster for a 5% mixture of ^{238}Pu in ^{239}Pu than for pure ^{239}Pu).

There are several ways of monitoring such deterioration and evaluating its possible effects on a weapon. One is to study samples of various ages in static experiments (see the figure). Another is to conduct dynamic experiments on subcritical amounts of plutonium (*6*) to determine the effects of aging on details of the compression and decompression states achieved when plutonium is shocked by high explo-

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sives. Such experiments provide criteria for determining when the primary stage of a weapon is no longer reliable because of plutonium aging.

There are many other kinds of specific data that must be obtained in order to maintain confidence in the nuclear deterrent. For example, physical and chemical effects of aging in metals and polymers can be accelerated through thermal cycling and experimentally monitored through repeated measurements. In parallel, the current program of surveillance of the existing stockpile is specifically addressing concerns about the physical degradation of components caused by corrosion. On the basis of this knowledge and without new data from underground nuclear tests, the leaders of the weapons laboratories will be able to continue meeting their formal responsibility, as they have done for the past 3 years, of annually informing the president whether the weapons in the nuclear stockpile remain safe and reliable. The key is getting and carefully validating the data.

Looking ahead to the longer term, new facilities are being established for improving experiments on, and therefore the fundamental understanding of, the physical processes occurring during nuclear explosions. A key aspect of this program is the Accelerated Strategic Computation Initiative (ASCI), which is to increase computer power in the near term by a factor of 10^3 or more. This will enable the development of high-fidelity, three-dimensional explosion codes with which to simulate a weapon under the extreme temperatures and pressures experienced during explosion, to analyze in far greater detail the data from previous nuclear tests, and therefore to better assess changes in weapon performance as a result of aging or altered remanufacturing procedures. These codes are replacing current simulations that rely on more phenomenological descriptions and on averaging approximations used to simplify the analyses. The codes will be validated against data from new facilities that recreate some of the physical conditions occurring during an explosion.

Indeed, one of the most important nonnuclear simulations of the primary stage is accomplished by hydrodynamic testing. The fissile material is replaced by nonfissile surrogates (such as tantalum or lead), and the behavior of the modified device is studied during implosion, right up to the point at which a nuclear chain reaction would normally be ignited. This is accomplished by a technique of dynamic radiography that relies on an intense beam of x-rays from a 20–megaelectron volt linear accelerator. Precisely timed x-ray pulses about 60 nanoseconds in duration and with a spot size of about 1 millimeter impinge on targets of high atomic number to yield bursts of gamma rays (about 10^2 roentgens at a distance of 1 meter) that give a high-resolution image of the implosion dynamics. A dual-axis radiographic hydrotest facility that produces two beams from two linear electron acccelerators at right angles, with multipulsing in one arm, is being constructed for this purpose at Los Alamos. It will provide more detailed information that is required for developing the basic understanding and code validation needed to maintain confidence in the stockpile over the long term. The important specific information to be gained includes the rate of convergence of the implosion (that is, its energy) and also its symmetry, which is critical for its efficient burn and integrity.

Another long-term source of valuable information is the National Ignition Facility (NIF), now under construction at Lawrence Livermore. This facility will allow experimental study of the inertial confinement fusion process through the delivery of a 1.8-megajoule laser pulse (divided among 192 beams) to excite temperatures above 3×10^6 K inside a hohlraum. Millimeter-sized pellets of fusionable material are symmetrically imploded inside the hohlraum in order to ignite thermonuclear fusion. This experiment simulates aspects of the secondary stage of a nuclear device explosion and also provides data on opacity, hydrodynamic behavior, and equations of state that are relevant to the primary stage. The predictions of the new codes developed by ASCI will be able to be checked against the NIF data.

The new information gained from this program is required in order to remanufacture weapon components that have degraded unacceptably because of aging or have been taken apart for detailed forensic study as part of the Stockpile Stewardship Program. The remanufacturing processes will often differ from those used in the original construction of the warhead, either because the original materials and industrial resources are no longer available or because of new environmental and safety regulations. The issue of remanufacturing did not come up during the era of underground testing, because this was also a period when new designs were being developed and could be counted on to replace aging weapons of older design. Manufacturing changes that reduce cost and enhance safety will also be encouraged, although strict discipline will be required to ensure that any changes in manufacturing techniques do not reduce confidence in the weapon (for example, by introducing new problems or uncertainties).

It is crucial to recognize, however, that without underground nuclear testing the data to be collected will not allow the development or production of "better" devices, in the sense of meaningful military improvements. No responsible weapon designer would certify the reliability, safety, and overall performance of a new design of a modern nuclear device without underground testing; and no responsible military officer would risk deploying or using such an untested weapon system.

Finally, no program of stewardship for the nuclear stockpile can be better than the quality of the scientists and engineers doing the work and providing the necessary leadership. An important consequence of the program that is currently in place is that, in addition to producing a large body of new data essential for maintaining confidence, it will provide challenging opportunities capable of attracting and retaining top-quality scientists and engineers within the nuclear weapons program.

Together with the current understanding of nuclear weapons gained from more than 1000 U.S. nuclear tests, including more than 150 involving modern designs during the past 25 years, we have a solid basis for placing high confidence in the reliability and safety of the U.S. nuclear stockpile in the near-term future. If improvements in command and control of delivery systems prove warranted, they can be made under the CTBT and possibilities for making them are supported by ongoing activities. Moreover, the experiments and simulations being performed over the coming years, as planned in the present program, are devised to yield clear warning signs of unanticipated problems should they arise.

References and Notes

1. The CTBT is a true zero-yield treaty, banning all explosions producing any self-sustaining nuclear fission reactions.
2. The weapon design laboratories are the Lawrence Livermore, Los Alamos, and Sandia National Laboratories.
3. The weapon production plants are Pantex (Amarillo, TX), AlliedSignal (Kansas City, MO), the Savannah River Site (Savannah River, SC), and Y-12 (Oak Ridge, TN).
4. Experiments will continue on the many nonnuclear components of the nuclear weapon systems.
5. These studies include JASON reports JSR-94-345 ("Science-Based Stockpile Stewardship"); JSR-95-320 ("Nuclear Testing") and its unclassified summary in the Congressional Record–Senate: S-11368 (4 August 1995); JSR-97-300 ("Subcritical Experiments"); JSR-97-320 ("Signatures of Aging"); and JSR-98-320 ("Signatures of Aging Revisited"), published by Mitre Corp., McLean, VA. In addition, S.D. chairs and R.J. and B.P. serve on the University of California's committee overseeing national security programs at the Los Alamos and Lawrence Livermore National Laboratories.
6. That is, configurations and amounts sufficiently small that the experiment remains truly zero yield.
7. Work of S. Conradson (Los Alamos National Laboratory) carried out at the Stanford Synchrotron Radiation Laboratory.