Nuclear Bunker Busters, Mini-Nukes, and the US Nuclear Stockpile

The Bush administration is contemplating a new crop of nuclear weapons that could reduce the threat to civilian populations. However, they're still unlikely to work without producing massive radioactive fallout, and their development might require a return to underground nuclear testing.

Robert W. Nelson

Congress is currently considering legislation that would authorize the US nuclear weapons laboratories to study new types of nuclear weapons: Earth-penetrating nuclear bunker busters designed to destroy hardened and deeply buried targets, and agent-defeat warheads intended to sterilize stockpiles of chemical or biological agents. In addition, the Bush administration has requested that Congress repeal a 1994 law, banning research that could lead to development of mini-nukes, low-yield nuclear warheads containing less than the power equivalent of a 5-kiloton chemical explosion, one-third that of the Hiroshima bomb.

The actual development of new nuclear weapons would require additional legislation and would signal a major policy reversal. The US has not developed a new nuclear warhead since 1988 and has not conducted a nuclear test since 1992. And although the Senate did not consent to ratify the Comprehensive Test Ban Treaty in 1999, the US continues to participate in a worldwide moratorium on underground nuclear testing. Currently, US nuclear weapons laboratories monitor and maintain the existing nuclear inventory through the Department of Energy's Stockpile Stewardship Program. (See Raymond Jeanloz's article in PHYSICS TODAY, December 2000, page 44.)

In support of its request to repeal the 1994 law, the Bush administration is arguing that the US may need lower yield nuclear weapons to more credibly deter rogue regimes possessing chemical, biological, or nuclear weapons. But arms control advocates fear that renewed US development of nuclear weapons would spark similar actions by other nuclear-armed nations and damage long-standing efforts to prevent the further proliferation of nuclear weapons. In addition, critics charge that mini-nukes blur the distinction between conventional and full-blown nuclear war and make the eventual use of nuclear weapons more likely.

Whether the US should go forward with actual development of new types of nuclear weapons will almost certainly be debated vigorously in Washington, DC for the next several years. Physicists and engineers have often participated in public debates over nuclear weapons policy, including new nuclear weapons development.[1,2] (See various related articles in PHYSICS TODAY, July 1975, November 1989, and March 1998.) More important, scientists can help policymakers to distinguish which technical goals are feasible and which are merely wishful thinking.

Robert Nelson *is a senior fellow for science and technology at the Council on Foreign Relations in New York City and a research staff member of the program on science and global security at Princeton University.*

Nuclear weapons advocates in the Bush administration favor missiles carrying nuclear warheads that could be designed to penetrate the ground sufficiently to destroy buried command bunkers or sterilize underground stocks of chemical and biological weapons and yet produce "minimal collateral damage." Crucial to the debate, therefore, is an understanding of the capabilities and limitations of earth-penetrating nuclear weapons. How deeply, for example, can missiles really burrow into reinforced concrete? How deeply buried must these weapons be for the surrounding rock to contain the blast? Would the underground temperatures of a nuclear blast sterilize chemical and biological agents?[3] This article addresses these questions and explains that the goal of minimal collateral damage falls squarely in the wishful-thinking category.

Conventional and nuclear earth penetrators

The US Department of Defense (DOD) has tens of thousands of conventional earth-penetrating weapons capable of destroying hardened targets like an underground bunker buried within 10 meters of the surface. As figure 1 illustrates, a typical 2.4-m laser-guided missile penetrates just a few meters into reinforced concrete and can create an explosion that leaves a 5-m-wide crater of material.

To supplement its supply of conventional penetrators, the DOD is also developing conventional agent-defeat warheads that combine the advantages of a hardened missile casing with a low-pressure incendiary warhead. Those weapons are designed to penetrate the interiors of a shallow-buried facility and then ignite a thermocorrosive filling that can maintain high temperatures for several minutes; the high temperatures and low pressures are meant to sterilize toxins and bioagents without dispersing them to the environment. The warhead may also release chlorine and other disinfecting gases to destroy any remaining biological agents.[4] To judge by the effectiveness of weapons used in the US wars in Afghanistan and Iraq, the precision, penetrating capability, and explosive power of conventional earth-penetrating weapons has improved dramatically over the past decade, and those trends are likely to continue.

Deeply buried and hardened structures, like a command and control bunker or a missile silo tens to hundreds of meters underground, are more immune to conventional explosives, though. Those structures are difficult to destroy even using an aboveground nuclear explosion: Until recently, the huge 9-megaton B-53 nuclear bomb was des-

Figure 1. This conventional laser-guided missile, after smashing into a hardened concrete bunker, penetrated 2–4 meters before detonating its 240-kg high-explosive warhead. Even the best earth-penetrating weapons reach depths of only about 6 meters. This explosion clearly was not contained by its surrounding cap of concrete. (Photos courtesy of the Defense Threat Reduction Agency.)

ignated to destroy such targets. Most nuclear weapons now in the US stockpile were designed to explode in the air or on contact with the ground. (For a brief summary of basic designs of nuclear weapons, see the box on page 34.) In either case, the blast wave transmits only a small fraction of the total yield as seismic energy into the ground; the large density difference between the air and the ground creates a mechanical impedance mismatch.

A nuclear device exploded just a few meters underground, by contrast, couples its energy more efficiently to ground motion and generates a much more intense and damaging seismic shock than would an air burst of the same yield. Figure 2 illustrates the dramatic change in equivalent yield. Exploding a 10-kt nuclear bomb at a depth of 2 m underground, for example, would increase the effective yield by a factor of about 20 and result in underground damage equivalent to that of a 200-kt weapon exploded at the surface.

To exploit that efficiency, in 1997 the US replaced its aging 9-megaton bombs with a lower-yield but earth-penetrating 300-kt model by putting the nuclear warhead from an earlier bomb design into a strengthened alloy-steel casing and a new nose cone. When dropped onto a dry lakebed from 12 km, the missile penetrated a modest 6 m. But even at this shallow depth a much higher proportion of the explosion energy would be transferred to ground shock compared to a surface burst at the same yield.

Were a bomb manufactured using even stronger materials and its mass increased using a dense internal ballast material—as proposed for the Robust Nuclear Earth Penetrator (RNEP), for instance—penetration depths could improve somewhat. (The Bush administration requested $15 million to study this improved penetrator.) However, figure 2 illustrates that those improvements would result in only modest gains in the total depth of destruction. Near the explosion, the peak pressure of the shock wave is proportional to the bomb yield and decreases with the inverse cube of the distance from the explosion. Consequently, the destructive effects of an explosion can be expressed as a function of a scaled distance, as is done in figure 2. Most of the benefit of earth penetration is obtained from the first (scaled) meter of burial.

Still, one might want maximum depth to help contain the blast. How deeply a missile can penetrate a target depends on the mechanical response of both missile and target at high dynamic stress levels. Generally, faster-moving missiles make deeper holes; that correlation is roughly linear up to speeds approaching 1 km/s. At higher velocities, however, the correlation breaks down as materials plastically deform and erode when the impact pressure from the target approaches the finite yield strength of the penetrator: $Y_p \approx \frac{1}{2}\rho_t v^2$ (see figure 3). The impact velocity of a missile made with even the hardest steel casing must remain less than a few km/s to avoid deformation.

Taking into account realistic materials strengths, 10–20 m is a rough ceiling on how deeply into dry rock a warhead can penetrate and still maintain its integrity.

Radioactive fallout

The 10 to 20-m range is far less than the burial depths needed to contain the radioactive fallout from even small nuclear explosions. Figure 4 illustrates the stark disparity in the numbers.[5] A 1-kt weapon, for example, must be buried at a depth of 90 m to be fully contained. Also shown is the destructive reach of a shallow-buried (10–20-m) bunker buster as a function of its yield—that is, how deep a target a given bomb could destroy. The seismic shock from the explosion can certainly destroy deeply buried targets. But weapons like the RNEP would still require very high yields (more than 100 kt) to destroy targets buried deeper than 100 m.

To appreciate the enhanced effect and the attendant dangers of a buried explosion, consider the sequence of events that follow detonation of a shallow-buried nuclear weapon, as diagrammed in figure 5. The explosion initially vaporizes the surrounding rock and produces a high-temperature cavity. The initial pressure of the cavity gases exceeds the pressure from overlayers of hard dirt and rock

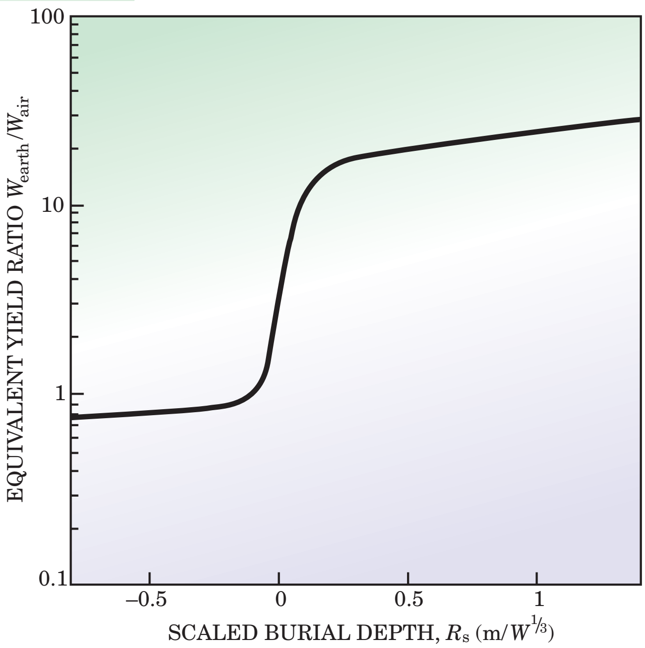

Figure 2. The equivalent yield ratio measures the seismic energy generated from a buried explosion compared to that of a surface burst as a function of the scaled depth, $R_s = R/W^{1/3}$, of the explosion. This scaling results from the variation of peak pressure with distance, $P \propto W/R^3$, where W is the total energy yield in kilotons. A bomb buried just 1 meter below the surface produces a ground shock more than an order of magnitude greater than an aboveground explosion. (Adapted from ref. 9.)

by many orders of magnitude. The cavity expands rapidly, sending outward a strong seismic shock that crushes and fractures rock.

Surface and shallow-buried nuclear explosions produce much more intense local radioactive fallout than an airburst, in which the fireball does not touch the ground.[6] When the blast breaks through the surface, it carries with it into the air large amounts of dirt and debris, made radioactive by the capture of neutrons from the nuclear detonation, as well as fission products from the bomb itself. The radioactive dust cloud produced in the blast does not rise as high as a classic mushroom cloud, but instead typically consists of a narrow column of vented hot gas surrounded by a broad base surge of ejecta and suspended fine particles, as shown in figure 6.

Casualties from an earth-penetrating nuclear weapon would be due primarily to ionizing radiation from the local fallout. The total number of fatalities due to radiation sickness depends on many factors: the population density, the local terrain and weather conditions, the time allowed to evacuate the area, and the radiation dose. But straightforward estimates based on empirically determined scaling laws show that anyone within the roughly $3W^{0.6}$ km^2 area covered by the base surge would receive a fatal dose of radiation.[3] (W is the explosive energy yield in kilotons of TNT.) For a typical third-world urban population density of 6000/km^2 those estimates imply that a 1-kt weapon would kill tens of thousands and a 100-kt weapon would kill hundreds of thousands of people.

Sanitizing stockpiles

High temperatures or intense radiation can destroy chemical or biological agents such as VX nerve gas or weaponized anthrax.[7,8] So, one might naturally imagine that the temperature and radiation levels produced in a nuclear explosion would be the ultimate germicide, atomizing shallow-buried stockpiles of chemical agents before they could disperse into the environment.[2]

It turns out, however, that most of the ejected crater material would be unheated and shielded from the initial burst of radiation. A nuclear blast of yield W would create a crater volume about $10^5\ W$ m^3, which disperses about ($2 \times 10^8\ W$) kilograms of debris.[6,9] If all of the $10^{12}\ W$ calories of energy from the nuclear explosion were distributed evenly, the mean energy available per unit mass totals about 5 kcal/kg—sufficient to raise the ejecta temperature by only 5–10°C.

Of course, the heat from the explosion is not evenly mixed, but is confined mainly to a small cavity of vapor-

A Nuclear Weapons Primer

A nuclear explosion begins with a chain reaction mediated by fast neutrons. Upon absorbing a neutron, a uranium-235 or plutonium-239 nucleus will usually fission into two lighter nuclei and two or more neutrons. The material has a critical mass if each neutron, on average, leads to the production of another neutron before it escapes or is absorbed by other processes. The rapid assembly of a supercritical mass of fissile material results in an exponentially growing number of neutrons—approximately 80 doublings in less than a microsecond—and an uncontrolled nuclear explosion.[13,14]

Two basic designs characterize fission weapons. A gun-type design uses a chemical explosive to propel one subcritical piece of highly enriched uranium into another to make a supercritical mass. The Hiroshima atomic bomb used that approach. An implosion design compresses a subcritical sphere of fissile material until it reaches high enough densities to become supercritical. The Nagasaki atomic bomb was triggered by such an explosion. To boost the yield of an implosion device, engineers introduce a mixture of tritium and deuterium gas. The gases undergo fusion and release a burst of high-energy neutrons that, in turn, induce additional fissions.

A thermonuclear (hydrogen-bomb) device uses a primary fission explosion to generate the high temperature and pressure required to ignite a secondary device containing both fusion fuel and a ^{238}U case. That secondary reaction releases a burst of high-energy neutrons that fission the uranium. Thermonuclear weapons can be much lighter and more powerful as a result. Most nuclear warheads in the current US stockpile are two-stage thermonuclear weapons equipped with an implosion-based Pu primary stage.

The total energy released in a nuclear explosion with a yield W kilotons (TNT equivalent) equals $10^{12}W$ calories, although the relative amounts of blast, heat, and direct nuclear radiation depend on the particular design. Some devices have a variable yield that can be adjusted just before launch.

The US currently has about 6500 strategic nuclear weapons with yields ranging from 5 to 1200 kt. Intercontinental ballistic missiles designed to target missile silos are examples. In addition, the stockpile contains about 1100 shorter-range tactical nuclear weapons; these include about 50 earth-penetrating B61-11 nuclear bombs,[15] with estimated yields ranging from 0.3 to 300 kt. The largest conventional bombs, in contrast, are 10-ton weapons, their yield limited by the weight of high explosives.

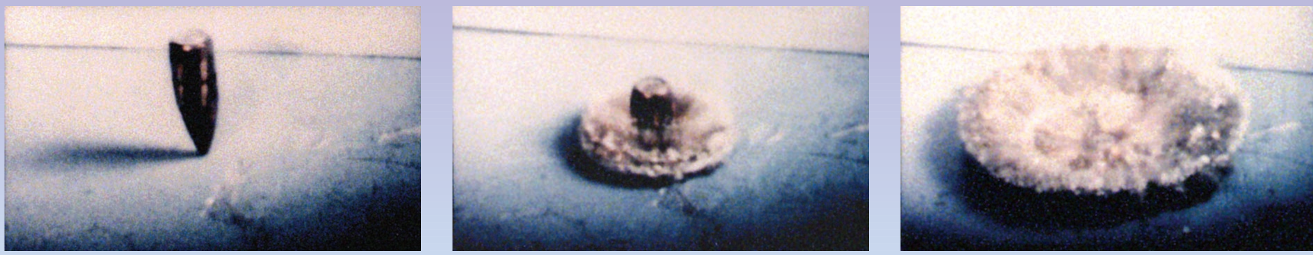

Figure 3. A copper and lead .30 caliber bullet liquefies as it strikes a steel plate at 850 meters per second. The transition occurs because the cohesive energy densities of such soft metals are insignificant compared to the impact pressures. Stronger materials can withstand higher velocity impacts, but even the hardest steel alloys cannot withstand smashing into rock or reinforced concrete at velocities greater than a few kilometers per second without deforming, fracturing, or even liquefying. (Photos courtesy of Heflin Steel Division of the ESCO Corp.)

ized rock and steam that expands and vents to the atmosphere. Because the mass density of soil or rock is roughly 2000 times greater than air, the radiation and high temperatures that are usually associated with a nuclear blast have a much shorter range in a buried explosion. In fact, nearly all of the neutron and gamma radiation are absorbed within just a few meters of the explosion.[3] Furthermore, although the initial temperature can exceed a million °C, the heat available to vaporize a cavity of rock extends only to a radius near $2W^{1/3}$ m, and the heat necessary to melt rock extends only to about twice that distance.[10]

As the cavity expands, the vaporized rock cools and condenses. For a contained explosion, such as the 1.7-kt Rainier test at the Nevada Test Site, the remaining gases are mainly superheated steam and carbon dioxide at temperatures less than 1500 K.[11] Beyond the cavity, the temperature falls off rapidly with distance, reaching the ambient ground temperature within a few cavity radii (see figure 7). Gases vented from within uncontained explosions cool even more rapidly.

Containers or munitions filled with chemical or biological agents that are within the final crater volume would be ruptured by the same strong ground shock that crushes the rock. But those agents are unlikely to suffer the high temperatures or radiation levels that would render them harmless unless they are very close to the nuclear weapon. More likely is that the cargo of still lethal chemical and biological toxins would mix with the fallout raining down from the main cloud or would be dispersed with the ejecta thrown out in the base surge.

A far more sensible strategy would be to ensure that whatever toxic material is already stored deep underground simply stays there. Once the entrances and exits to toxic storage facilities were sealed up using conventional tactics and the territory captured, the agents could be safely neutralized.

To test or not to test

If Congress does eventually authorize the development of new nuclear weapons, will the US have to resume underground nuclear testing in order to certify its warheads? The answer depends on the design in question, but in most cases nuclear testing would be unnecessary.

Nearly all the components of a nuclear weapon, including the implosion of its plutonium core, can be tested absent a nuclear explosion. The testing engineers simply replace the fissile material with a chemically identical isotope that does not produce a chain reaction—the weapon performs nearly every step, but does not deliver a nuclear yield. That method should be sufficient to test previously certified designs under new conditions and allow engineers to safely judge the performance of weapons that would experience the severe shock of earth penetrators.

If Congress were to opt for low-yield nuclear weapons, nuclear testing could again be bypassed because of the flexibility already built into existing warheads. Indeed, every modern warhead in the US nuclear arsenal has a

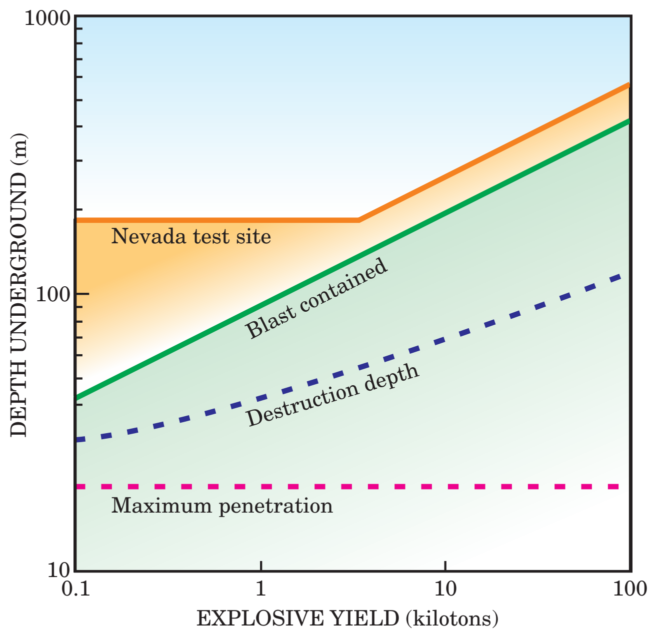

Figure 4. Containing a nuclear blast underground requires that a bomb be buried at a distance that depends on the explosive yield. The green line indicates the depth required to completely shield the surface from the blast. Engineers testing underground explosions at the Nevada Test Site buried bombs deeper still (orange line). Yields as low as 0.1 kiloton would need at least 43 meters of ground coverage to fully contain the explosion, but that depth is already much greater than the theoretical 20-m maximum penetration depth of the most robust missile (dashed red line). Also shown is the depth of destruction achievable from a shallow-buried bunker buster of given energy (dashed purple curve). Very high-yield explosions (more than 100 kt) with their extensive radioactive fallout are needed to destroy structures buried more than 100 m.

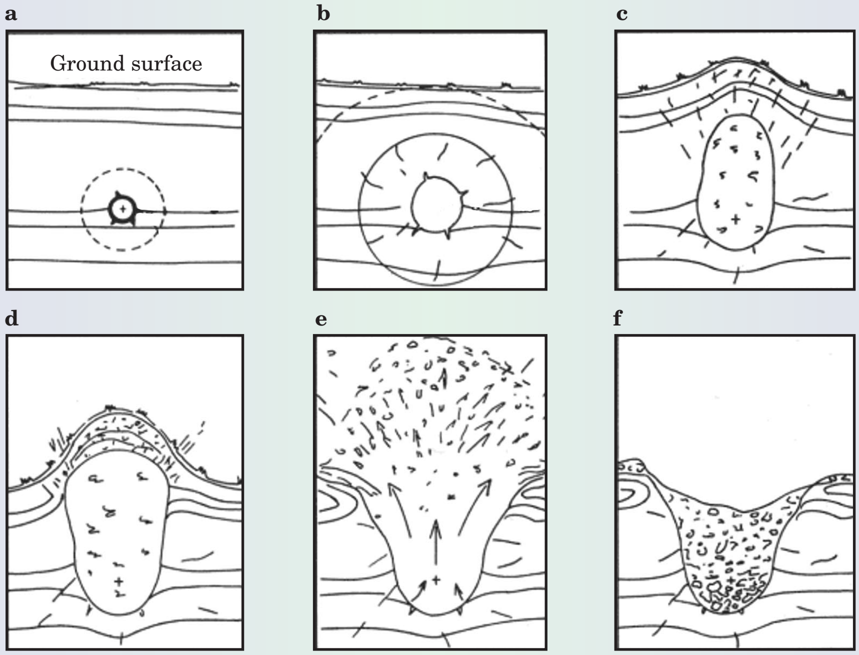

Figure 5. A shallow-buried underground nuclear explosion. **(a–b)** The nuclear detonation generates a strong shock wave that vaporizes a cavity of rock with an initial radius $2W^{1/3}$ m and melts rock out to roughly twice this distance. **(c–f)** There is little post-shock heating beyond the melt radius, but the shock is strong enough to crush rock approximately 12 times farther away, at $50W^{1/3}$ m. The cavity gases continue to cool rapidly as the cavity expands. A combination of gas acceleration and the compression and rarefaction phases of the seismic wave throws materials out of the crater at the surface.[16] (Adapted from ref. 17.)

low-yield mode. By disconnecting the secondary stage of the thermonuclear reaction and reducing (or eliminating) the phase that boosts the deuterium–tritium gas, a nuclear weapon in the arsenal could be converted into an unboosted primary fission weapon that delivers a subkiloton yield.

Gun-type designs, described in the box on page 34, are so simple and robust—one subcritical piece of highly enriched uranium (HEU) is propelled into another to make a supercritical mass—that they would also require no testing. Unfortunately, would-be nuclear terrorists are also likely to recognize the simplicity of those devices. To minimize the likelihood of nuclear terrorism, therefore, the number of locations in the world where HEU can be found should be greatly reduced.

But if Congress were to authorize the nuclear weapons laboratories at Los Alamos and Lawrence Livermore to pursue a completely new design—an implosion device using a boosted primary—the inherent uncertainties in warhead performance would almost certainly require that the weapon be fully tested before being certi-

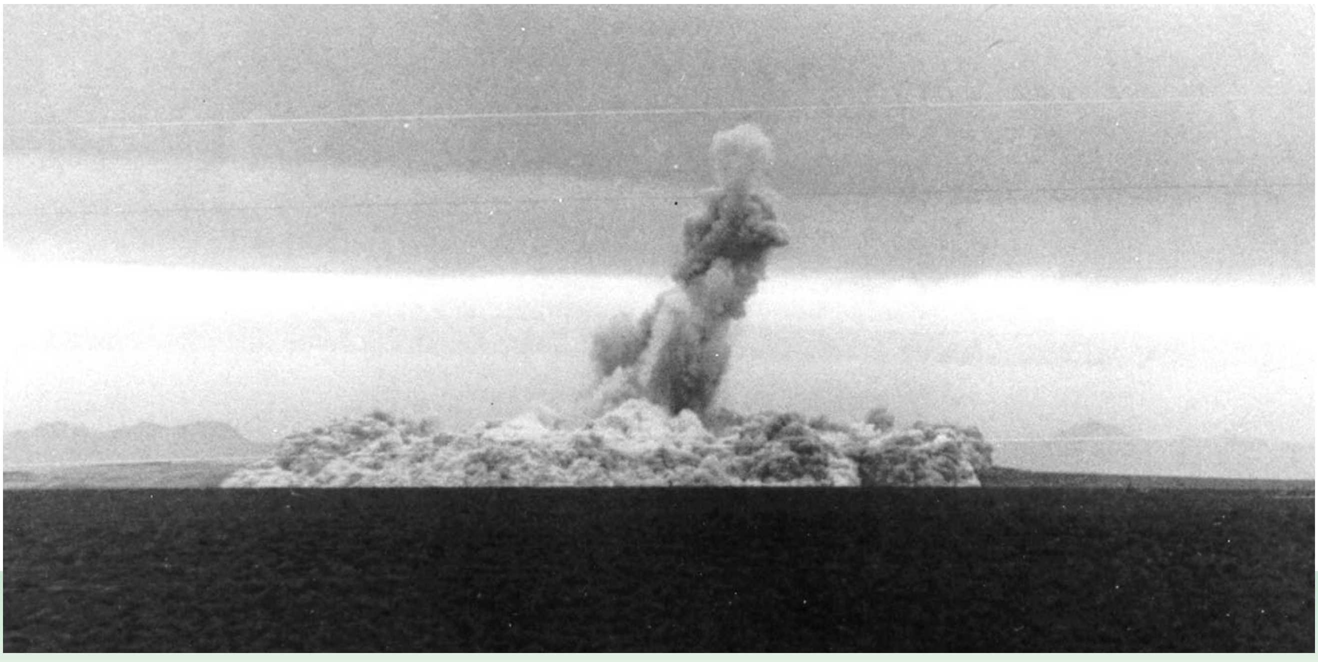

Figure 6. The low-yield (2.3-kiloton) "Cabriolet" nuclear test at the Nevada Test Site, north of Las Vegas. Engineers buried the warhead 52 meters under hard compressed rocky soil—much deeper than could be reached by an earth penetrator. The highly radioactive base surge reached a diameter of approximately 2.5 kilometers. (Photo courtesy of the US Department of Energy/National Nuclear Security Administration.)

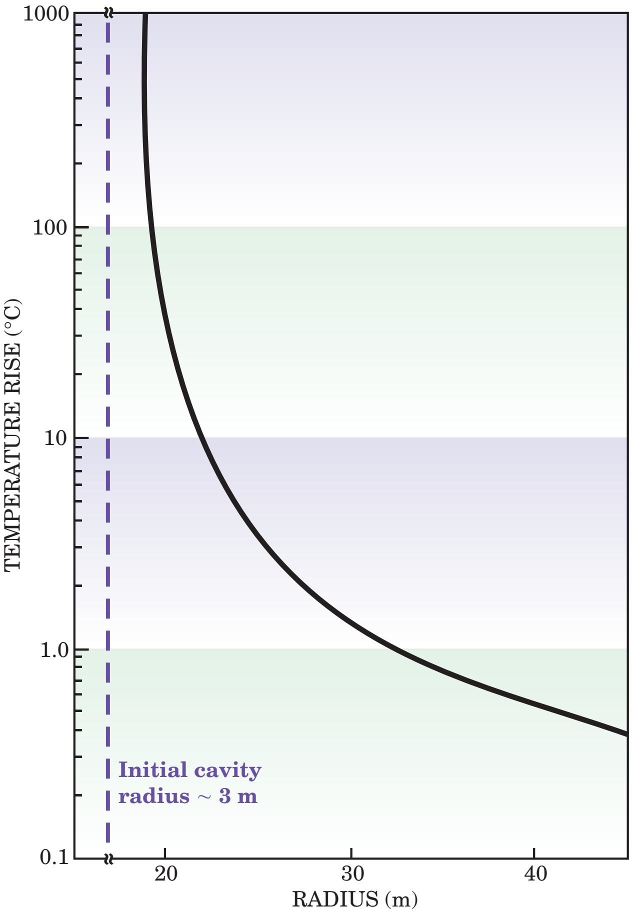

Figure 7. The temperature distribution outside of the contained 1.7-kiloton Rainier test 90 milliseconds after the explosion. Although rock located beyond several radii of the area vaporized by an underground blast is thoroughly crushed or fractured, very little of it is heated much above ambient temperature. Hypothetical stockpiles of chemical or biological agents well beyond the cavity would not be sterilized because all but the closest regions (within one to three times the initial cavity radius) are insulated from heating. (Adapted from ref. 11.)

fied to enter the US stockpile.[12] Such a decision would have profound consequences.

Since the end of the cold war, nuclear weapons have receded in importance; high-precision conventional weapons can now accomplish many missions that until recently would have required nuclear yields. Were the US to research and develop new types of nuclear warheads for the kinds of missions discussed here—bunker busting or targeting chemical stockpiles—the course change would surely signal a renewed US belief that nuclear weapons have a broad range of potential uses. In response, wouldn't foreign nations have a powerful incentive to develop or improve their own nuclear deterrent?

Were the US to resume underground nuclear testing, it is highly likely that Russia, China, and other countries would resume their own programs as well. Those nations could improve their own nuclear arsenals far more than would the US, if there was a return to testing. Such a breakdown in the moratorium would destroy near-term prospects of entry into force of a comprehensive test ban and profoundly undermine efforts to limit nuclear proliferation.

I thank Frank von Hippel for originally suggesting this project and for his thoughtful guidance. I also acknowledge helpful conversations with Sidney Drell, Harold Feiveson, Steve Fetter, Richard Garwin, Raymond Jeanloz, Scott Kemp, Zack Halderman, Michael Levi, Michael May, and Greg Mello.

References

1. S. Drell, J. Goodby, R. Jeanloz, R. Peurifoy, *Arms Control Today* **33**, 8 (2003).
2. See the article by J. E. Gover and P. G. Huray in *IEEE Spectrum Online* at http://www.spectrum.ieee.org/WEBONLY/resource/mar03/speak.html.
3. For a more technical description, see R. W. Nelson, *Sci. Global Secur.* **10**, 1 (2002) and R. W. Nelson, *Sci. Global Secur.* (in press), and M. May, Z. Haldeman, *Sci. Global Secur.* (in press).
4. For a more detailed description, see the report *HTI-J-1000 High Temperature Incendiary J-1000*. Available online at http://www.globalsecurity.org/military/systems/munitions/hti.htm.
5. US Congress, Office of Technology Assessment, *The Containment of Underground Nuclear Explosions*, rep. no. OTA-ISC-414, US Government Printing Office, Washington DC (October 1989). Available online at http://www.wws.princeton.edu/cgi-bin/byteserv.prl/~ota/disk1/1989/8909/8909.PDF.
6. S. Glasstone, P. J. Dolan, eds., *The Effects of Nuclear Weapons*, US Government Printing Office, Washington, DC (1977).
7. National Research Council, US Committee on Review and Evaluation of Alternative Technologies for Demilitarization of Assembled Chemical Weapons: Phase II, *Analysis of Engineering Design Studies for Demilitarization of Assembled Chemical Weapons at Pueblo Chemical Depot*, National Academy Press, Washington, DC (2001).
8. H. Kruger, *Radiation-Neutralization of Stored Biological Warfare Agents with Low-Yield Nuclear Warheads*, rep. no. UCRL-ID-140193, U. of California, Lawrence Livermore National Laboratory, Livermore, Calif. (2000). Available online at http://www.llnl.gov/tid/lof/documents/pdf/238391.pdf.
9. J. A. Northrop, ed., *Handbook of Nuclear Weapon Effects: Calculational Tools Abstracted from DWSA's Effects Manual One (EM-1)*, Defense Weapons Special Agency, Washington, DC (1996).
10. T. R. Butkovich, *Calculation of the Shock Wave From an Underground Nuclear Explosion in Granite*, rep. no. UCRL-7762 Reprint-1965-4-l, U. of California, Lawrence Livermore National Laboratory, Livermore, Calif. (1967). Available online at http://www.llnl.gov/tid/lof/documents/pdf/19093.pdf.
11. R. A. Heckman, *Deposition of Thermal Energy by Nuclear Explosives*, rep. no. UCRL-7801, U. of California, Lawrence Radiation Laboratory, Livermore, Calif. (1964). Available online at http://www.llnl.gov/tid/lof/documents/pdf/19111.pdf.
12. National Academy of Sciences, *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty*, National Academy Press, Washington, DC (2002).
13. R. Serber, R. Rhodes, *The Los Alamos Primer: The First Lectures on How to Build an Atomic Bomb*, U. of Calif. Press, Berkeley (1992).
14. S. Glasstone, P. J. Dolan, *The Effects of Nuclear Weapons*, US Department of Defense and US Department of Energy, Washington, DC (1977).
15. R. S. Norris, W. Arkin, H. Kristensen, J. Handler, *Bull. At. Sci.* **59**, 73 (2003).
16. N. M. Short, *The Definition of True Crater Dimensions by Post-Shot Drilling*, rep. no. UCRL-7787, U. of California, Lawrence Radiation Laboratory, Livermore, Calif. (1964).
17. E. Teller, *The Constructive Uses of Nuclear Explosives*, McGraw-Hill, New York (1968). ■