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Nuclear and Non-Nuclear Options for Counter-proliferation

Michael A. Levi

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INTRODUCTION

At the end of the Gulf War, many military thinkers began to argue that precision-guided munitions had made tactical nuclear weapons obsolete. Television images of bombs threaded into buildings made graphic the revolutionary advances in guidance technology. With weapons that exploded within meters of their target, the massive destructive radii of nuclear weapons had become unnecessary.

But before long new rationales for tactical nuclear weapons appeared. Reacting to America's military revolution (and to some extent Israel's attack on Osirak a decade earlier), Iraq and others began to build underground, where their facilities were easier to conceal and harder to destroy. The proliferation of chemical and biological weapons, often built in apparently typical industrial facilities, presented new challenges for finding targets and avoiding collateral damage during attack. Nuclear weapons designers identified these requirements as potential missions for new nuclear weapons.

In a 1991 article in *Strategic Review*, "Countering the Well-Armed Tyrant,"[1] Thomas Dowler and Joseph Howard II gave specific proposals for new nuclear weapons. A 10-ton ground-penetrating "micro-nuke," 1,000 times smaller than the bomb dropped on Hiroshima, could be used to destroy hardened and deeply buried targets (HDBT) and could counter facilities containing chemical and biological agents. These weapons, they argued, would prevent the risk of escalation into a larger nuclear war, both because their targets would not be nuclear-armed and because their relatively small size would distinguish them from their massive strategic nuclear brethren. Furthermore, they argued, such weapons would greatly reduce the nuclear fallout that had previously precluded the use of nuclear weapons.

In 1993, responding to pressure to develop such new nuclear weapons, Congress passed the Furse-Spratt amendment to the 1994 Defense Authorization Act, which banned any research and development that would lead to a new nuclear weapon with a yield of less than 5 kilotons. At the time of this writing (October 2002), a conference committee on the 2003 Defense Authorization Act is debating whether to partially repeal this ban.

In 1997 the United States developed its first "low-yield" bunker-killing nuclear bomb, the B-61 mod 11, which modified the most common U.S. nuclear bomb so that it would survive the shock of penetrating the earth. The weapon's primary purpose was to replace the B-53, an aging 9-megaton

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[1] Thomas Dowler and Joseph Howard II, "Countering the Threat of the Well-Armed Tyrant: A Modest Proposal for Small Nuclear Weapons," *Strategic Review*, Fall (1991), vol. 19, issue 4, pp. 34–40.

bomb designed to destroy Soviet missile silos. The new bomb was designed to detonate underground with a yield of 300 kilotons—20 times the yield of the bomb used at Hiroshima. But the new bomb could also allow detonation with a yield of 340 tons, more than 30 times smaller than the Hiroshima bomb.

In March 2002, portions of the U.S. Nuclear Posture Review leaked to the public revealed renewed interest in developing a range of specialized nuclear weapons. The review identified capability shortfalls in attacking HDBT, and facilities containing weapons of mass destruction (WMD); it suggested that nuclear weapons might have unique capabilities to address these threats. The review revealed a new program to build a Robust Nuclear Earth Penetrator, a modified nuclear weapon designed to destroy deeply buried targets. But it went further, noting, "Nuclear weapons could be employed against targets able to withstand non-nuclear attack (for example, deep underground bunkers or bio-weapon facilities)." Ultimately, however, the posture review is noncommittal, leaving open a crucial question: Do the military advantages gained by developing new nuclear weapons offset the liabilities of development or use of new nuclear weapons?

The development or use of tactical nuclear weapons entails many downsides. Crossing the nuclear threshold, regardless of the size of weapon used, would be an irreversible step that would weaken nonproliferation regimes. New weapons might require nuclear testing, which would break America's self-imposed testing moratorium and weaken international norms against the testing of nuclear weapons. However, many argue that the military advantages to be gained by building new nuclear weapons outweigh these liabilities. To help illuminate this conflict, this paper explores the military capabilities that development of new nuclear weapons might deliver, and compares them with what might be obtained by aggressive pursuit of non-nuclear capabilities.

After reviewing our ability to locate underground targets, we turn to the capabilities of nuclear and non-nuclear weapons to defeat them. Our review points to six main conclusions:

- Large nuclear weapons have unique destructive abilities unmatched by even the most advanced non-nuclear weapons.
- A large class of potential underground tunneled facilities cannot be destroyed either by existing or future nuclear weapons.
- Research and development on new non-nuclear technologies has resulted in conventional weapons whose military effects are comparable to those of small nuclear weapons.
- Detonated in an urban area, any nuclear weapon of substantial destructive power will cause very large numbers of civilian casualties.
- Detonated against an isolated non-urban facility, many nuclear weapons will produce radioactive fallout that would substantially interfere with movements of friendly troops.
- Functional defeat, whereby a facility is not directly destroyed but is rendered inoperable, will be necessary to counter deeply tunneled facilities.

Simple destruction of facilities containing WMD may be insufficient if dispersal of the agents causes substantial collateral damage. We analyze weapons that might neutralize chemical and biological agents, thus limiting collateral damage. Our comparison of nuclear and non-nuclear options reaches five main conclusions:

- Non-nuclear weapons can have capabilities against biological agents comparable to those of small nuclear weapons.
- Nuclear weapons can neutralize chemical and biological agents in underground facilities even if they must be detonated outside the target facility.
- It is uncertain whether fallout from nuclear weapons that detonate outside target facilities will be more or less dangerous to civilians than dispersal of live biological agents from inside the target facility. Regardless of which effect dominates, the collateral damage of an attack will be great if the facility is in or near an urban area.
- Fallout from nuclear attacks on chemical or biological weapons facilities will produce greater impediments to the movement of friendly troops than the dispersal of live chemical or biological agents from non-nuclear attacks on the same facilities, assuming troops wear typical protective gear.
- Small nuclear weapons detonated inside facilities of concern have unique capabilities for simultaneous neutralization of chemical and biological agents. If they consistently achieve precise yields, and if they are used against deeply buried facilities, they would avoid spreading substantial nuclear fallout.

We find, furthermore, that excessive constraints on current non-nuclear programs for addressing HDBT and WMD problems could lead to otherwise avoidable shortfalls in important capabilities. We recommend that planners:

- Stress Intelligence: Since adversaries can dig deeply and can hide WMD activities in industrial settings, simple pursuit of powerful weapons will never solve the HDBT and agent-defeat problems. The ability to locate and characterize threat facilities is the foundation of any efforts in this area, and must be our first priority.
- Use Air Supremacy: Many current programs for HDBT defeat are unnecessarily constrained by requirements that all weapons deliverable by tactical fighter jet, or that target destruction be accomplished in a single aircraft pass. These requirements do not allow weapons designers to take full advantage of American air superiority, and such constraints should not be applied to weapons development.
- Focus on Biological Agents: Our current approach seeks a single weapon that can neutralize both chemical and biological agents. But while biological agents are much more strategically important targets, chemical agents are much harder to destroy. Our present approach leads to shortfalls in our ability to neutralize biological agents because the requirement that the same technology be able to destroy chemical agents unnecessarily constrains it.
- Evaluate Weapons in Context: While conventional weapons are tested in war-games and affirmed with military chiefs, nuclear weapons often are not vetted as thoroughly. The valuable taboo against the use of nuclear weapons perversely shields these weapons from the same scrutiny during their development that all other weapons receive. If civilian leaders decide to consider pursuit of new nuclear weapons, uniformed military personnel must confront these weapons concepts with the same scrutiny they apply to other weapons systems.

TARGET FACILITIES AND THEIR DETECTION

Hard and Deeply Buried Targets

The July 2001 *Report to Congress on the Defeat of Hard and Deeply Buried Targets* identifies these as "structures ranging from hardened surface bunker complexes to deep tunnels." HDBT are of particular concern because they often house command and control, leadership, or WMD. The facilities can be classified into three types, based on facility construction.

The first class consists of those built near the earth's surface and surrounded by reinforced concrete walls, usually of less than 5 meters' thickness. According to the Departments of Energy and Defense, such facilities make up the majority of the world's HDBT.[2] These bunkers are built using "cut-and-cover" methods: earth is removed, a reinforced concrete bunker is built in the open hole, and rock or dirt fills in the remaining space. Cut-and-cover bunkers can extend over hundreds of square meters and are typically buried at depths of less than 30 meters.[3]

The second class consists of facilities tunneled into rock or earth but not located far beneath the surface. The prototypical example of a facility in this class is the Libyan Tarhunah chemical production facility, reported to be tunneled under 18 meters of earth.[4] What distinguishes these facilities from the previous class is not their hardness, but that, since they are tunneled rather than built in the open and then covered, they are far more difficult to localize. They can be built using traditional drilling or blasting techniques or more modern tunneling equipment.[5] Alternatively, an adversary might use natural caves, as Al Qaeda did in Afghanistan.

A third class of facilities consists of underground complexes tunneled into rock and buried deeply. These facilities differ from the second class simply by their depth—earth-penetrating weapons cannot directly penetrate facilities in this class. Their depths range from 20 meters to more than 1 kilometer.[6] Deep tunnels, in contrast with the tunnels in the second class, are often dug sideways into the base of a mountain, rather than down from the earth's surface. Like those in the second class, these tunnels may also be natural.

Many have argued that the possibility of enemies digging deep, hardened facilities presents a new threat. For example, William Schneider, now head of the Defense Science Board, wrote recently that Iraq was exploiting "advances in tunneling technology" to dig deeper underground. Such claims are misleading—deep tunnels have been dug for centuries[7] using blasting methods, and there are few technical limits on the depths that rogue regimes can tunnel. New tunneling technology offers

2 "Report to Congress on the Defeat of Hard and Deeply Buried Targets," Departments of Energy and Defense (July 2001).

3 Eric M. Sepp, "Deeply Buried Facilities: Implications for Military Operations," Occasional Paper No. 14 (Center for Strategy and Technology, Air War College, May 2000).

4 Geoffrey Forden, "USA Looks at Nuclear Role in Bunker Busting," *Jane's Intelligence Review,* January (2002). Online at www.janes.com/press/pc020312_1.shtml.

5 Sepp, "Deeply Buried Facilities: Implications for Military Operations," pp. 6–10.

6 The *Report to Congress on the Defeat of Hard and Deeply Buried Targets* (p. 9) says such facilities have "a concrete overburden equivalent of 70 to 300 feet," but there is no reason to believe that facilities are not located deeper than that. Indeed, Soviet and U.S. command and control facilities are buried at greater depths.

7 For an enlightening description of 19th century tunneling technology, see, for example, Stephen Ambrose, *Nothing Like It in the World* (New York: Simon & Schuster, 2000), pp. 199–202.

adversaries safer drilling (unlikely to be important to rogue regimes) and quieter operations, a challenge to U.S. intelligence but not a new challenge to American weapons capabilities.

Finding and Characterizing Underground Targets

The task of defeating HDBT is highly demanding of intelligence. For both nuclear and non-nuclear weapons, the less powerful but more precise weapons require accurate mapping and characterization of specific targets. Methods for detecting underground facilities fall into two categories.

Construction Detection. Construction detection methods are applied while a facility is being built. They involve monitoring changes in the observable environment, such as the buildup of excavated rock or the slumping of ground above a new tunnel. However, construction detection relies on a requirement that intelligence assets be focused on the threat area during facility construction. A facility built while its host state is not an enemy, or while HDBT construction is not suspected, may go undetected and only later become threatening. Construction detection is further limited when natural underground formations or preexisting mines are used, because in these instances there would be little construction to detect. Only activities associated with tailoring the underground facility to its eventual use might be detected.

Operations Detection. Methods that detect functioning facilities either detect the structure of a facility or discern activities within the structure. Structure detection methods identify surface and umbilical features (power lines, access tunnels, entrance portals) of a facility, or directly identify the facility itself. These methods, applied any time after the facility has been constructed, are limited mainly by detection technology. In particular, technology often requires access near the facility, although the need for forces to remain in the area might be eliminated if clandestine sensors, which would transmit to remote analysis platforms, were dropped near a suspected facility.

While a facility is functioning, several sorts of activities can be detected, and many technologies may be applied to identify access points. Sensors can monitor either specific events, such as the entry or exit of individuals from the facility, or continuous properties of the facility's operation, such as the functioning of electrical power lines and venting of air. Other technologies can detect activities in the bunker itself, such as the operation of machinery.

Effective integration of information from different sources will be crucial. No single technology will be a panacea for facility detection, and human intelligence will be important. Coordination of these systems will challenge attempts to hide a facility. We describe five technologies and their technical limitations:[8]

Hyperspectral Imaging. Hyperspectral imagery, collected by satellite or airborne vehicle, is a sophisticated extension of visual or infrared overhead imagery. The technique examines 100 to 250

[8] For an excellent discussion of underground facility detection, see W. Happer et al., "Characterization of Underground Facilities" (MITRE Corporation, April 1999).

bands over a large part of the electromagnetic spectrum[9] and thus reveals details that would be indistinguishable simply by examining the visible part of the spectrum. Objects camouflaged in one part of the light spectrum may not be camouflaged in other parts of the spectrum. Thus, for example, the entrance to a tunnel hidden by leaves might not be apparent in visual satellite imagery, but might be in a hyperspectral image; the same image would also distinguish the electromagnetic spectrum reflected by leaves covering a tunnel entrance from that of leaves simply covering underlying rock. Hyperspectral techniques are still, however, limited by the requirement that the observer be able to directly see the object of interest—for example, a tunnel entrance beneath a 10-meter granite overhang would be undetectable.

Seismic Sensing. Oil and gas prospectors have developed seismic imaging methods[10] that can produce useful images of underground facilities at depths greater than 100 meters.[11] Such techniques use geophones—sensitive tools that can detect very weak waves in earth—to identify and locate underground facilities.

In one type of application, these systems are used to detect vibrations from machinery operating in underground facilities. According to a recent study, such methods can detect operation of facilities at a distance of 20 to 60 meters in soil and 40 to 120 meters in rock.[12]

In another application, a controlled source of seismic waves (most likely an explosion) is used; through the distortion of the waves produced by a facility, geophone sensors infer the location and characteristics of the underground facility, much as a sonogram images the interior of the body. This technology holds an advantage over attempting to detect vibrations from facility operation in its ability to image weapons-storage facilities or facilities whose equipment is very quiet.

Electromagnetic Detection. Electromagnetic sensing[13] can be used to detect a facility's power lines by sensing the characteristic magnetic fields the lines produce. Existing instruments can sense lines as far as 40 kilometers away. They have a 5-meter surface resolution for observations made from 100 meters' altitude, and they can detect power lines 100 meters underground. While the sensors cannot be operated from satellites, they can be operated from unmanned aerial vehicles. One limitation of electromagnetic sensing is that it would be useless against primitive facilities without outside power, such as the caves Al Qaeda used in Afghanistan.

Synthetic Aperture Radar. Perhaps the most promising approach to detecting entrances is synthetic aperture radar. Normally, the ground surface reflects radar signals, which are registered in a receiver.

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9 In contrast, color film collects information from three parts of the optical portion of the electromagnetic spectrum: red, green, and blue. Information on hyperspectral imaging is available from the U.S. Geological Survey at http://biology.usgs.gov/hwsc/hymas.html.

10 This section is based on material from Happer et al., "Characterization of Underground Facilities."

11 Sepp, "Deeply Buried Facilities: Implications for Military Operations," p. 16.

12 Because ambient noise limits geophone resolution, this probably represents the limit of usefulness for this technology. The precise limit, however, will depend on the strength of the seismic signal being measured.

13 Happer et al., "Characterization of Underground Facilities," pp. 17–19.

In the presence of a tunnel or other long, narrow opening (an adit), the reflected signal is delayed by its traversal of the adit, appearing as an artifact in the radar image. Processing these images with specially designed filters may automate detection of adits. However, imagery must be collected from low-flying aircraft, rather than satellite, which presents some challenges.

Gravimetry and Gravity Gradiometry. Because the strength of the earth's gravitational field varies over its surface depending on the density of the material underneath the surface (usually rock), the presence of a hollowed-out bunker or tunnel causes a minute but measurable difference in the force of gravity at the surface. Sensitive gravimeters (used to prospect for mines) can detect these fluctuations. Until recently this process was slow and painstaking, but the advent of global positioning systems (GPS) has greatly improved it. A further enhancement has been the integration of gravimeters with inertial measurement units. The device resulting from this combination is known as a gradiometer and can quickly and dynamically measure gravitational changes. Current sensors can identify tunnels of 5-meter radius at 45-meter depth in rock from 100-meter height.[14] Detectors currently under development are expected to detect similar tunnels at 350-meter depth from similar height, or, alternatively, tunnels at 45-meter depth from 400-meter height. However, these may not be small enough for practical use.

Identifying Weapons of Mass Destruction Targets

Identifying targets associated with WMD as opposed to legitimate commercial activities is immensely challenging. Human intelligence will be even more essential than it is in efforts to locate facilities underground. This is evidenced, for example, by United Nations inspectors' past failure to find Iraqi biological weapons, despite intrusive inspections.

Sensor approaches hold some promise, particularly in detecting chemical weapons, which are much easier to identify than biological weapons. The same sensors now being developed for homeland defense and troop protection might be employed to detect agents from biological and chemical weapons production facilities. However, at this point, detecting chemical or biological weapons will depend on leakage of agents or production-related chemicals from poorly sealed plants. Thus, adversaries may be able to counter sensor-based approaches by tightly sealing their production and storage facilities and by incinerating waste that might emanate from facilities.

DEFEAT OF HARD AND DEEPLY BURIED TARGETS

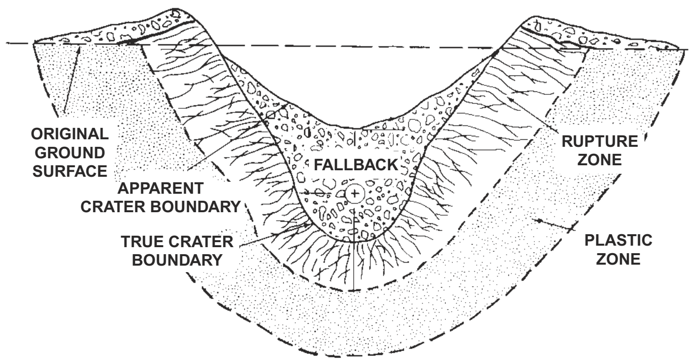
Nuclear Weapons

A nuclear weapon detonated at or near the earth's surface produces a large crater and sends a massive shock wave into the ground. Underground facilities within this crater are destroyed, as are facilities slightly outside it where strong stresses rupture the earth[15] (Figure 1). The radius of this roughly

[14] Happer et al., "Characterization of Underground Facilities," p. 45.

[15] Vibrations will damage or destroy equipment in poorly built facilities beyond this zone. This is not, however, a reliable destructive mechanism; one would not be likely to know before an attack whether the facility had been hardened against vibrations, and would not be able to verify after an attack whether the equipment in a facility had actually been destroyed.

Figure 1. Damage produced by an earth-penetrating nuclear weapon



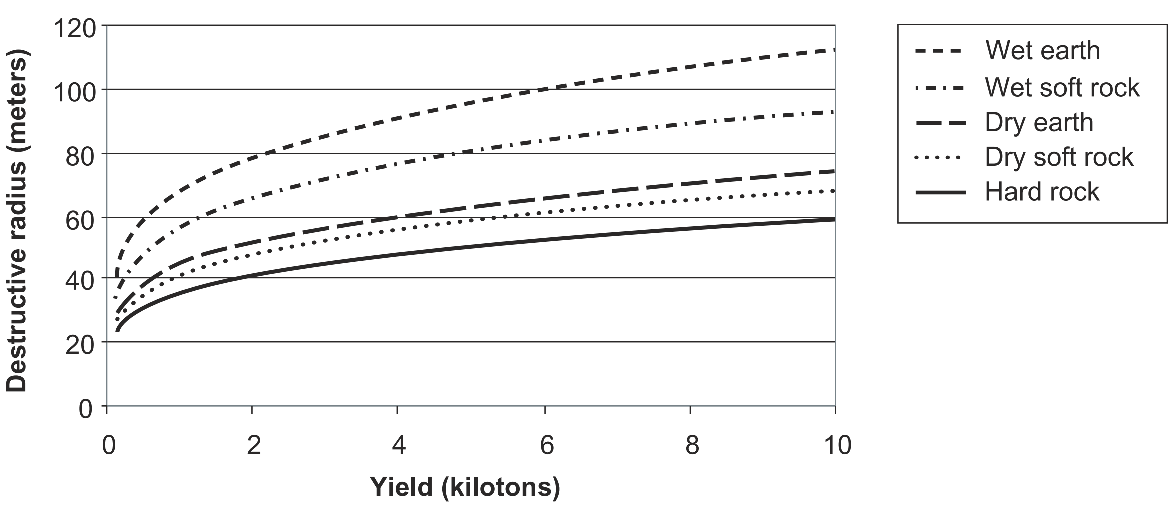
All facilities in the crater or in the rupture zone would be destroyed.

hemispherical destruction zone depends on ground composition, weapon yield, and detonation depth. Consider a weapon detonated at a depth of 5 meters. Figures 2 and 3 show how the radius of destruction varies with ground composition and weapon yields between 100 tons and 1 megaton.

The ability of a given bomb to destroy a target depends on how far from the target the bomb detonates, which, in turn, depends on the precision of the weapon and on how closely intelligence locates the target. Consider a facility tunneled beneath 20 meters of granite: Figure 4 shows the relationship between weapon yield required and distance of detonation from the target—as the distance from the target increases, the nuclear yield required for destruction rises quickly.

Shallow but hardened underground facilities may also be vulnerable to the shock wave produced by a nuclear weapon detonated aboveground. Consider the facility depicted in Figure 5: It is 12 meters wide and 7 meters deep, surrounded by 2 meters of reinforced concrete, and buried under 2 meters of earth.[16]

Figure 2. Destructive radius for nuclear weapon detonated 5 meters underground: 0.1 kT to 10 kT



Note that the destructive radius of detonation increases only slowly with increasing explosive power. Also, the destructive radius is significantly larger in saturated materials.

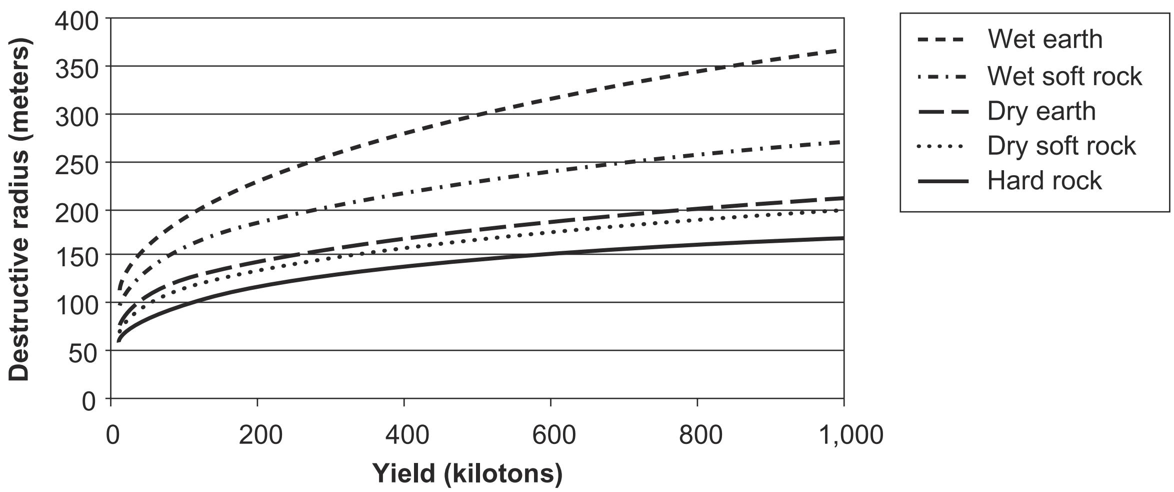
[16] Much of this analysis is based on John Farrel et al., "Target Vulnerability and Uncertainty Analysis," prepared for the Defense Nuclear Agency (January 31, 1977).

To collapse this target, a 1-kiloton weapon detonated at the surface[17] must be within 35 meters of the target; a 10-kiloton weapon, within 90 meters of the target; and a 1-megaton weapon, within 600 meters.

Use of nuclear weapons against underground bunkers would result in substantial radioactive fallout, which could cause collateral civilian damage and impede friendly military forces.

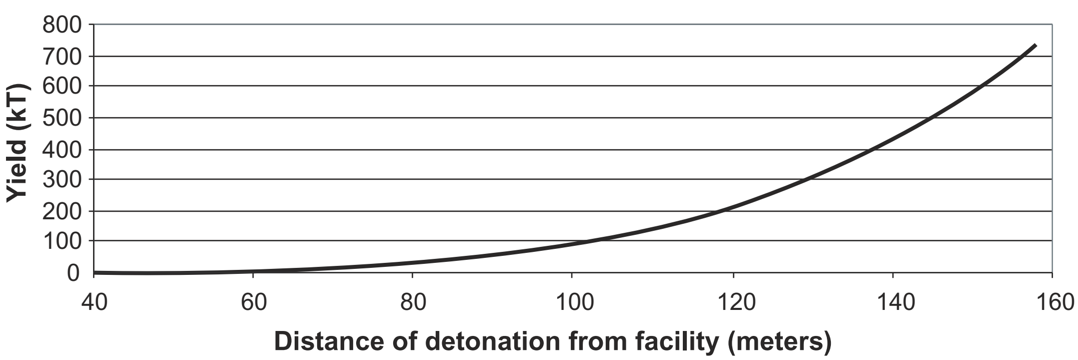
For an earth-penetrating nuclear weapon detonated in a city, potential civilian casualties from fallout have been calculated.[18] Figures 6 and 7 show estimates for the area over which all people

Figure 3. Destructive radius for nuclear weapon detonated 5 meters underground: 10 kT to 1 MT



Note that the destructive radius increases only slowly with increasing explosive power. Also, the destructive radius is significantly larger in saturated materials.

Figure 4. Nuclear yield required for weapon detonated 10 meters underground to destroy facility under 20 meters of granite

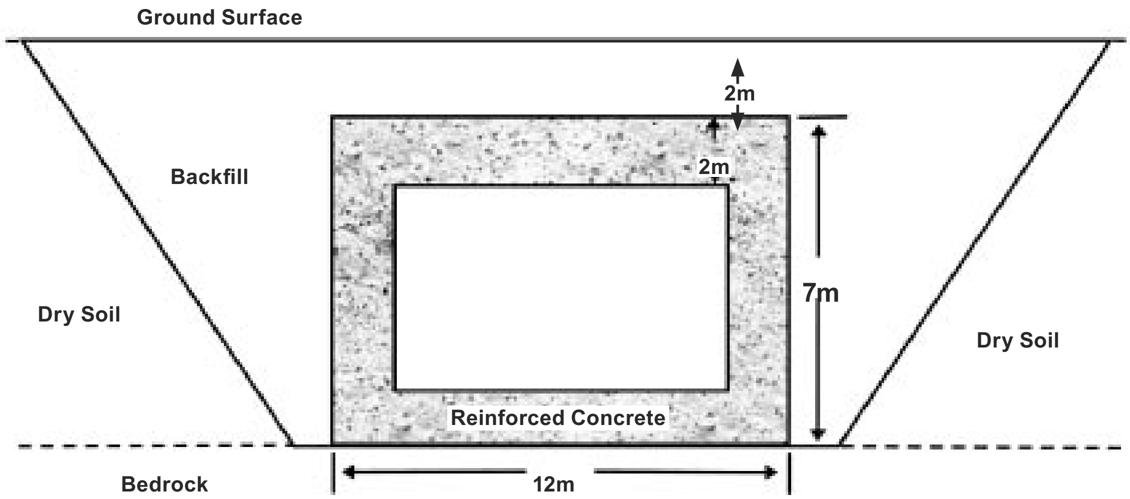


Note that as the weapon-to-bunker distance increases, the yield required increases quickly. The yield required at a distance of 40 meters is 1 kiloton.

17 Ground penetration is of little additional use here—see Samuel Glasstone and Phillip J. Dolan, *The Effects of Nuclear Weapons*, 3rd edition (U.S. DOD and DOE, 1977), p. 258.

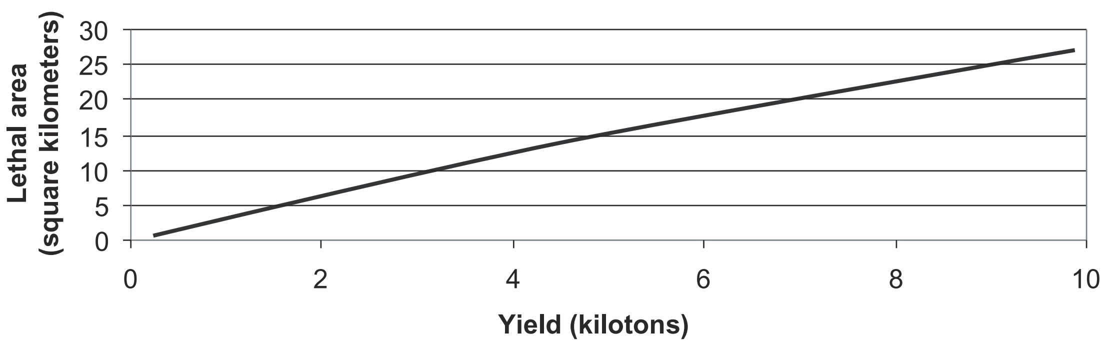
18 Robert W. Nelson, "Low-Yield Earth Penetrating Nuclear Weapons," *Science and Global Security*, vol. 10 (2002), pp. 1–20.

Figure 5. Typical cut-and-cover bunker



An area is dug out of the surrounding soil, the reinforced concrete bunker is built in the open pit, and the dug-out area is filled in.

Figure 6. Approximate area of 100% fatalities for earth-penetrating nuclear weapon 200 T to 10 kT

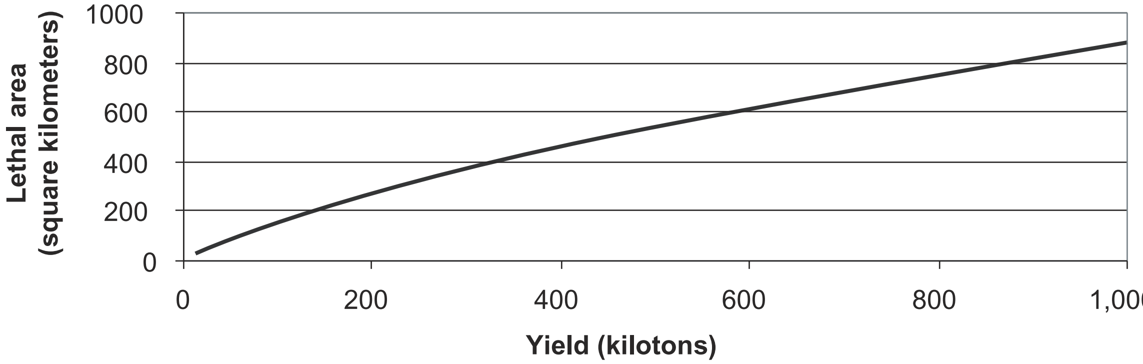


For a shallow underground nuclear detonation, a large lethal radioactive cloud would form. Here, we use conservative assumptions about evacuation and containment, as described in the text.

would be expected to die from fallout, assuming that: the weapon detonates near the earth's surface; early fallout occurs within a half hour of detonation; evacuation takes place within three hours; and 30 percent of radioactive materials produced by the nuclear weapon fall to earth quickly. These assumptions are very conservative—the lethal area might be substantially larger. Still, the results are striking: for a 1-kiloton bomb detonated in a dense urban area, deaths would number in the several tens of thousands.

Collateral damage would differ if the bomb were detonated outside a city. For example, consider a 1-kiloton bunker-busting fission bomb detonated 5 meters underground in 10-mile-per-hour wind, which could destroy facilities buried under nearly 20 meters of granite. Consequently, as far as 3

Figure 7. Approximate area of 100% fatalities for earth-penetrating nuclear weapon 10 kT to 1 MT



For a shallow underground nuclear detonation, a large lethal radioactive cloud would form. Here, we use conservative assumptions about evacuation and containment, as described in the text. The definition of "shallow" depends on the yield of the weapon: For a 1-MT blast, detonation 50 meters underground would be considered shallow.

kilometers downwind, all residents not evacuated would receive a fatal dose of radiation; as far as 5 kilometers downwind, 50 percent of those not evacuated would soon die of radiation poisoning; and for some residents acute death from radiation poisoning could occur as far as 8 kilometers downwind. For a 1-megaton explosion, deaths would be expected 100 kilometers downwind if residents were unable to evacuate quickly.

Over a wider area, although outright fatalities might not occur, radioactive contamination could render territory uninhabitable. The area abandoned will depend on the level of increased cancer risk residents are willing to accept. To estimate what that area might be, assume that people are willing to return to an area only if the radiation exposure is less than the maximum received by a radiation worker.[19] Since radioactivity decays over time, different areas will be uninhabitable for different lengths of time. If a 1-kiloton bomb were detonated 5 meters underground in 10-kilometer-per-hour wind, people as far as 10 kilometers downwind from the blast would have to wait one year before returning to the area; 6 kilometers downwind, the area would have to be abandoned for 2 years; and 3 kilometers downwind, residents would be able to return only after 5 years.

A 1-megaton blast under 10 meters of granite, while destroying facilities buried almost 200 meters underground, would contaminate a much larger area. Assuming the same weather conditions and willingness to return as above, for some areas 240 kilometers downwind from the blast, people would have to wait 1 year before returning; 100 kilometers downwind, the area would have to be abandoned for 5 years; and 15 kilometers downwind, residents could return only after 25 years.[20]

Tactical circumstances may force friendly troops to accept a greater radiation risk than civilians will. Nevertheless, earth-penetrating nuclear weapons could render significant areas of a battlefield

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19 If exposed 20 years at this rate, one's chance of dying of cancer would rise from 20 percent to 24 percent.

20 The maximum dose permitted for radiation workers in a 1-year period is 5 rem. The Defense Nuclear Agency's Effects of Nuclear Weapons codes were used to calculate initial fallout dispersal.

Table 1. Downwind extent of the contaminated area after a 1-kiloton nuclear blast 5 meters underground, for different reentry times

	Level of Acceptable Risk		
	Willing to accept moderate risk	**Willing to accept emergency risk**	**Willing to accept chance of fatalities**
Entry one hour after attack	14 km	10 km	6 km
Entry one day after attack	4 km	3 km	2 km
Entry four days after attack	1.8 km	1.5 km	1 km

Table 2. Downwind extent of the contaminated area after a 1-megaton nuclear blast 10 meters underground, for different reentry times

	Level of Acceptable Risk		
	Willing to accept moderate risk	**Willing to accept emergency risk**	**Willing to accept chance of fatalities**
Entry one hour after attack	16 km[a]	16 km	16 km
Entry one day after attack	140 km	100 km	55 km
Entry four days after attack	40 km	30 km	None[b]

[a] This counterintuitive result arises because after one hour, the wind has only been able to carry fallout 16 kilometers downwind. Of course, troops would be unlikely to enter an area where they expected fallout to soon arrive.

[b] This counterintuitive result arises because the large nuclear explosion spreads its massive fallout over a wide area.

off limits; calculations shown in Tables 1 and 2 illustrate the significant complications that would result from nuclear use against underground targets. Army guidance categorizes troops according to the amount of radiation they are exposed to.[21] The area excluded to troops depends on the level of radiation risk they are willing to tolerate and on how long they wait before entering the area, since radioactivity decays with time. Table 1 illustrates the exclusion zones for dismounted infantry for different entry times and risk tolerance if a 1-kiloton nuclear weapon were detonated 5 meters underground in 10-mile-per-hour wind. Table 2 shows the exclusion zone if a 1-megaton weapon were detonated 10 meters underground, as would be required to destroy a facility under 200 meters of granite.

[21] *NBC Field Manual*, United States Army (October 6, 2000), Chapter 4. Moderate risk is defined as a total radiation dose of 50 to 70 rem; emergency risk, 70 to 150 rem; and some short-term radiation death, more than 150 rem.

Table 3. Conventional earth penetrators in the current U.S. arsenal

Earth Penetrator	Length	Penetration Abilities
BLU-109	8 feet	More than 6 feet of reinforced concrete
BLU-113	19 feet	More than 20 feet of concrete and more than 100 feet of earth
BLU-116	8 feet	More than 12 feet of reinforced concrete and more than 50 feet of earth; can survive impact in hard rock

Non-Nuclear Weapons

Earth-penetrating weapons are long, slender bombs that penetrate the ground before detonating. To be effective, they usually must penetrate the interior of a target bunker.

Kinetic Penetrators. Kinetic penetrators use their momentum of impact to tunnel through earth, rock, or concrete. Penetration ability is determined by several factors, including the density of the penetrator material, the hardness of the target material, the speed at which the penetrator impacts the earth, and the length of the penetrator. The penetration abilities of weapons in the current U.S. arsenal are described in Table 3.

The most capable penetrator in the current arsenal—the BLU-113—has no propulsion and impacts the ground from gravity alone at approximately 450 meters per second. Increasing impact velocity can significantly improve penetration depth, and, in theory, a penetrator similar to the BLU-113 could impact hard rock or reinforced concrete at speeds of 900 meters per second without being destroyed. Propelling this bomb to 900 meters per second would increase its penetration depth in hard rock by 75 percent, more than double its penetration depth in concrete and soft rock, and would multiply its penetration depth in soil nearly tenfold. Above 900 meters per second, impact would severely deform the penetrating weapon and prevent it from carrying a payload to its target.

One way to increase impact speed is to add rocket propulsion; the resulting weapon is known as a boosted penetrator. Boosted penetrators can, as a rule, achieve impact speeds of 750 meters per second while carrying significant payloads.[22] Such improvements would increase the BLU-113's penetration depth in concrete by approximately 50 percent.

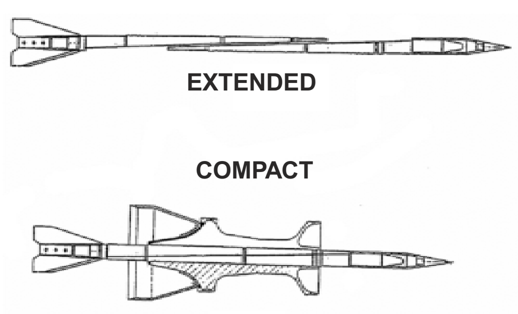
To further increase impact speed and thus penetration depth, intercontinental ballistic missiles (ICBMs) or submarine-launched ballistic missiles (SLBMs) equipped with conventional penetrator warheads, rather than with nuclear weapons, are the most promising option. Such missiles can easily achieve the necessary impact speed for maximum penetration; in fact, braking mechanisms will likely be necessary to ensure that their payload does not impact at speeds too high for the warhead to withstand. Existing ICBMs can deliver one-ton payloads, implying that a single converted ICBM might be able to deliver several BLU-116–type penetrators.

[22] Nancy Swinford and Dean Kudlick, "A Hard and Deeply Buried Target Defeat Concept" (Sunnyvale: Lockheed Martin Missiles and Space, 1996).

Use of conventional ICBMs or SLBMs would entail significant political complications. Since these missiles are traditionally associated with nuclear weapons, a launch of such missiles could lead other countries—Russia, in particular—to falsely believe that the United States was initiating a nuclear attack. Several proposals have been made to avoid this. Some[23] have suggested launching all missiles over the South Pole on trajectories that could not possibly reach Russian territory. Others suggest situating conventional ICBMs at launch fields separate from nuclear ICBMs. Yet another possibility would be to replace all ICBMs with conventional warheads. (This would of course require a substantial change in American nuclear posture, abandoning the doctrine of a strategic triad.) Such a replacement could be implemented as part of the Strategic Offensive Reductions Treaty (SORT); eliminating all nuclear ICBM warheads would reduce the U.S. nuclear force by 1,700 warheads to a level still far above the 1,700 to 2,200 set by the SORT.

Increasing the length of a penetrating weapon increases the depth to which it can penetrate the earth. Thus, penetrators longer than those in the current U.S. stockpile would improve penetration capabilities. There are, however, several practical impediments to lengthening these weapons. First, the weapon must be short enough to be delivered by an appropriate aircraft. The requirement that nine different types of fighter jet be able to deliver the BLU-116 penetrator constrains its length. In contrast, only an F-15E fighter jet can deliver the BLU-113 penetrator, which can penetrate more than twice as deep. Also, as penetrator length increases, steering and structural integrity become more difficult to maintain. One possibility for circumventing both these constraints might be an extending penetrator (Figure 8),[24] carried in collapsed form and extended just before impact. Such a weapon can increase its length immediately before impact, potentially delivering a several fold increase in penetration depth. The main barrier to developing such a system is the severe difficulty in unfolding the penetrator in flight, an engineering challenge that has yet to be surmounted.

Figure 8. The extending penetrator in extended and compact positions



The concept can yield significant increases in penetration depth while still fitting into an appropriate delivery vehicle. The penetrator is launched in the “Compact” form, and converts to the “Extended” form shortly before impact.

Small Diameter Bomb. A major difference between nuclear and conventional weapons is nuclear bombs’ greater radius of destruction. For example, a 10-meter-radius bunker buried under 10 meters of earth could be destroyed by a single conventional penetrator only if its location were precisely known. If, for example, the bunker’s location could be determined only to within 40 meters, a penetrating weapon targeted at such a large area would probably miss the actual facility.[25] In contrast, a 1-kiloton nuclear weapon detonated at the center of a 40-

23 Paul Robinson, “Pursuing a New Nuclear Weapons Policy for the 21st Century,” White Paper (Sandia National Laboratory, 2001). Online at www.sandia.gov/media/whitepaper/2001-04-Robinson.htm.

24 William Rosset, “An Overview of Novel Penetrator Technology” (Aberdeen Proving Ground Army Research Lab, February 2001), pp. 7–12.

25 The probability of a single weapon destroying the facility would be roughly 6 percent, the ratio of facility area to the area within which intelligence can locate the facility.

meter circle within which the bunker could be located would give nearly 100 percent confidence that the facility would be destroyed.

The small diameter bomb (SDB), a weapon concept the Air Force is currently developing, would address this problem. The new bomb would be the same length but much narrower than the GBU-32 penetrating weapon. It would weigh just 250 pounds, half the weight of the smallest bomb currently in the Air Force arsenal. Since the penetration depth of a weapon depends on its length but not its diameter, these smaller bombs would have the same penetration ability as the current GBU-32 penetrators. Yet given their small size, 24 small diameter bombs will fit in the same space in an F-22 fighter jet that would otherwise be occupied by 6 GBU-32 penetrators. Dropping 24 penetrating bombs over the area suspected to contain the target bunker described above would increase the probability of destroying the target facility to nearly 100 percent. The main drawback of the SDB concept is that each individual bomb will carry a substantially reduced payload.

Active Penetrators. Previously discussed weapons penetrate the earth through impact momentum. Active penetrators operate more like drills, burrowing into the ground with rapid strikes before detonating. The prototypical example of this, currently under development, is Deep Digger.[26] While it is not yet known whether Deep Digger will be developed into an effective weapon, it demonstrates the potential of exotic penetrating technologies.

Deep Digger would operate on principles very similar to "dry drilling" techniques the oil and gas industries developed in the United States years ago; full-scale dry drilling machines drill to depths of 4 kilometers. These machines use a metallic head to repeatedly and rapidly pulverize rock, which is cleared from the mineshaft throughout operation by pressure from high-density gas.

Deep Digger would function in much the same way, but would be much smaller; instead of weighing thousands of tons, it is designed to weigh 50 to 100 kilograms. Such a device would be extremely portable and could be delivered either by special operations forces or by aircraft.

Deep Digger engineers report that initial technical difficulties involved pulverizing the target rock into fine matter, but this problem has largely been overcome. In its current developmental state, Deep Digger creates a clean bore in rock 1 meter deep and 20 centimeters wide. Deep Digger now reduces target rock to very fine powder that is ejected by gas to heights of approximately 50 meters.

Payloads. For bunker-killing weapons, techniques must be developed to ensure that the payload detonates in the target bunker, not before or after it passes through that area. The recently deployed hard target smart fuse (HTSF)[27] offers unprecedented ability to do this. The HTSF uses sensors that count earth layers and empty voids, detonating after it breaches a predetermined number of layers or after it enters an empty area, likely a bunker. The reliability of the HTSF is still in question, and further improvements will be required to destroy targets more consistently.

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[26] Deep Digger material, from Josh Kellar of FAS, is based on interviews with Deep Digger designer Shyke Goldstein of Advanced Power Technologies Inc.

[27] See the Air Force Research Laboratory's Ordnance Division at: www.mn.afrl.af.mil/public/ordnance.html.

If a penetrator reaches the targeted bunker and detonates there, the bunker can be destroyed by means of a range of payload options. For use against command and control facilities, a thermobaric payload will probably be most effective.[28] Thermobaric weapons are specialized explosives designed to operate in closed spaces such as tunnels and bunkers. They provide long burn times and sustained high pressures while minimizing peak blast overpressure relative to typical conventional explosives.

Fuel-air explosives (FAE) may also be effective. These weapons work by dispersing a cloud of fuel before igniting it. Such weapons do not deliver the same peak blast force of conventional explosives, but they can sustain substantial pressure over a much longer period and larger area than conventional weapons. Inside a bunker, spreading the fuel before ignition also will help mitigate the effects of barriers and corners that might otherwise protect parts of the bunker from single-point explosions. FAE can produce more than 10 times as much energy for a given payload mass than conventional explosives, such as TNT.

Precision Guidance. To be effective, all of the conventional approaches described require a high level of precision. The most advanced precision-delivery systems in the current U.S. arsenal are the Enhanced Guided Bomb Unit-28 (EGBU-28) and the Joint Direct Attack Munition (JDAM). Before the EGBU-28 is dropped, either someone in an aircraft or an observer on the ground places a laser marker on its target. A receiving unit on the bomb detects the laser and corrects the bomb's course to guide itself to the target. Rain, snow, fog, low clouds, smoke, dust, and debris can all impair the efficacy of laser-guided bombs by blocking or scattering the laser light; in particular, in cloudy conditions, ground forces are essential for marking the target with the laser. In the terminal phase of its flight, the EGBU-28 uses GPS guidance to direct itself to the target, resulting in an accuracy of 1 to 3 meters.[29]

The JDAM uses GPS and an inertial navigation system (INS) to deliver a 1,000- or 2,000-pound bomb to its target. The INS system measures speed and acceleration as the missile travels to its target, and adjusts the missile's course and speed so it stays on target. When GPS is active, JDAM has an accuracy of 13 meters. If GPS is jammed, JDAM maintains an accuracy of 30 meters using only its INS. A yet-to-be-determined terminal guidance system may be developed to improve JDAM precision to 3 meters.

Further improvements in precision beyond 1- to 3-meter accuracy are unlikely to be useful, since the destructive radius of weapons will be significantly larger than the errors in detonation point.

Functional Defeat. When a facility cannot be attacked directly or when military or political constraints preclude such an attack, functional defeat may be employed. Such techniques, while not eliminating the facility, seek to disable it or isolate it from the outside world. This can be done either

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28 Adam Hebert, "DOD Readies 'Thermobaric' Cave-Clearing Bomb for Enduring Freedom," *Inside the Air Force*, January 4 (2002).

29 Accuracy is measured here by circular error probable (CEP). The CEP of a weapon is the radius of the circle within which a given weapon can be expected to fall 50 percent of the time.

physically, by sealing entrances, or, for command and control facilities, by breaking communications links to the outside. Even when physical destruction of a facility is possible, functional defeat may be preferable, allowing U.S. forces to retrieve crucial intelligence information by examining a facility's intact contents.

Developing intelligence methods to detect entrances and umbilical features will be crucial for functional defeat of underground targets. As discussed above, the intelligence means to detect surface features are more easily developed than the means to detect actual facilities. A frequent contention is that, for full functional defeat, detection ease is offset by the requirement to find all entrances, whereas, for physical defeat, finding the facility is the only requirement. This is misleading—just as many entrances to a single facility may have to be defeated, so, many widely separated facilities associated with a single entrance may each have to be attacked separately.

Once entrances and other features have been identified, they can be destroyed with conventional weapons. Typically, explosives-carrying cruise missiles are the weapon of choice to attack tunnel entrances. If the entrance is penetrated, thermobaric weapons, which send a high-pressure shock wave down the length of a tunnel, can also be used to extensively damage the inside of the facility without sealing the entrance. However, this approach could be defeated by a series of doors along the tunnel that would block the shock wave.

Power and communications lines may also be targets of attack. Destroying electrical lines could disable production equipment and ventilation systems necessary to the survival of a facility's inhabitants. Any crucial facility is likely to have backup generators for power, but inhabitants will not be able to depend on these for extended periods. Damaging communications lines or radio transmitters and receivers would cut off those in command and control bunkers, preventing them from directing military or other operations.

A variation on functional defeat is based on the information umbrella concept.[30] In some cases, it is impossible to locate all exits from an underground facility. The information umbrella approach confronts this by training a wide spectrum of sensors on the area thought to contain the exits, and identifying exits as they are used. U.S. forces would wait for equipment to exit the facility, identify it, and destroy it. Such an approach would probably rely on miniaturized sensors dropped in the vicinity of suspected exits and on autonomous units, such as armed unmanned aerial vehicles, which could promptly destroy anything leaving the underground facility. Non-persistent land mines activated by the sensor system or lingering cruise missiles could also be used.

Functional defeat of a buried facility could also be achieved by disabling its electronic equipment. While much of U.S. research into electronic weapons remains classified, information about the Pentagon-sponsored British E-bomb has recently been publicized. The E-bomb is a microwave weapon that mimics the effects of the electromagnetic pulse of a nuclear blast, disabling electronic equipment with a surge of electricity more damaging than a lightning blast. Because the pulse can travel down a bunker's power and ventilation ducts, equipment in buried targets is vulnerable to attack. Cruise missiles can deliver E-bombs.

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[30] Joseph Nye and William Owens, "America's Information Edge," *Foreign Affairs*, March/April (1996), pp. 20–36.

DEFEAT OF CHEMICAL AND BIOLOGICAL AGENTS

One of the most frequently offered rationales for the use of nuclear weapons against hard targets is that they would destroy the chemical or biological weapons inside, thus mitigating collateral damage. We begin this section by evaluating this claim.

Nuclear Weapons

Nuclear weapons can destroy chemical and biological agents through two mechanisms: incineration—raising the temperature of the target agents for an extended period—and irradiation—exposing the target agents to an intolerable amount of radiation. Also contributing to the effectiveness of nuclear weapons is that the blast produced by detonation breaks agents out of their containers, exposing them to more heat or radiation. In almost all instances, radiation alone will be insufficient to neutralize biological and chemical agents.[31] We thus only discuss defeat of agents by incineration.

Weapons might be detonated underground but not inside the target facility. Data on partially contained underground nuclear explosions are scant, but available evidence suggests that the entire rupture zone (see Figure 1) surrounding an underground nuclear detonation may be within the nuclear fireball, and thus raised to a temperature of at least 1,000 degrees Celsius;[32] this is more than sufficient to destroy all chemical and biological agents. Since this is also the zone of complete destruction for underground nuclear detonations, we would expect the agents in destroyed facilities to also be neutralized.

For poorly designed underground facilities in soft rock or earth, damage may extend beyond the rupture zone, even though the fireball does not extend that far; in such cases, live agents may be released into the atmosphere. Additionally, since analysis of this scenario must be based on very limited experimental data (the Partial Test Ban Treaty prohibits new nuclear cratering experiments), military planners could have little confidence that no live agents would be dispersed.

If a nuclear weapon can be detonated inside the target facility, a much smaller yield weapon might be used. For example, a 10-ton nuclear weapon would produce a fireball of approximately 20-meter diameter,[33] over which temperatures would be raised above 3,000 degrees Celsius. At temperatures this high, agent containers, as well as barrier walls less than several meters thick, are likely to be destroyed, along with their biological or chemical weapon contents. Effects beyond the

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31 Two illuminating research papers from Lawrence Livermore National Laboratory's Hans Kruger ("Radiation Neutralization of Stored Biological Agents with Low-Yield Nuclear Warheads," August 21, 2000, and "Delayed Fission Debris Radiation Effects on Chemical and Biological Agents Stored in a Bunker," 1998) explore chemical and biological weapon destruction via prompt nuclear radiation and via radiation from the radioactive debris produced by the nuclear explosion. Comparing Kruger's results with those presented here for heat-related neutralization indicates that there are no advantages to be gained through using nuclear radiation as a killing mechanism.

32 Forden ("USA Looks at Nuclear Role in Bunker Busting") writes that the rupture zone surrounding a buried nuclear explosion is usually charred, suggesting that the fireball penetrates this rupture zone. If it does, then all the agents in that zone, the same as the zone of physical destruction, would be neutralized. The charring, however, could be due to flash burns, burning in areas exposed to radiation from the fireball but not to the fireball itself. In that case, the fireball would not have penetrated the rupture zone, implying that agent containers there might be broken open without neutralizing the agents contained.

33 We use the radius for an air-burst fireball. The effect of cavity confinement will likely be to slightly increase this size.

fireball are more difficult to predict, and if the defender blocks off portions of the facility with heavy, insulating walls, agents beyond those walls are unlikely to be neutralized.[34]

To minimize collateral damage, it would be desirable if the nuclear weapon did not break open the top of the bunker. Would a 10-ton weapon detonated at the center of a well-built bunker the size of its fireball break open that facility? This would depend on the bunker's depth. A bunker just below the ground surface would certainly collapse, whereas one beneath 15 meters of reinforced concrete would likely remain intact. For bunkers at depths in between, survival would depend on the integrity of the bunker's construction. In addition, if the weapon were detonated near the edge of the facility rather than at its center[35] or if the facility were smaller than expected, the bunker would be more likely to collapse, releasing radioactive debris.

Certainty as to the weapon's nuclear yield will also be essential because unexpected overshoots in explosive power could release large amounts of radioactive fallout. Nuclear weapons are exquisitely tuned instruments, and very low-yield bombs are likely to be particularly sensitive. Building a weapon robust enough to sustain the impact shock an earth-penetrating weapon must endure will be challenging, and confidence in such a weapon would be unlikely without nuclear testing.

Some have suggested that nuclear weapons might be used to spread radioactive debris through a facility without collapsing it, thus effectively disabling the facility by rendering it unusable. But calculations indicate that any bomb big enough to contaminate a bunker for several weeks would also be big enough to destroy all of the facility's contents.[36] The area-denial effect would then be irrelevant, because denying access to a facility whose contents have already been destroyed is redundant.

Radiological Weapons

Another option might be to drop radiological materials into a bunker.[37] Radiological weapons are not effective military weapons when used in open spaces, because the spreading of radioactive materials dilutes them to a point where the radiation they emit is not a threat. Dispersal in a confined space, however, would be more effective. Dispersing 2,500 curies of cobalt-60 powder would probably be sufficient to deny use of a 40- by 40-meter bunker. Radioactive contamination in the facility would produce dose rates sufficient to kill in a few hours, and, unlike with nuclear weapons, the contamination would last several years.[38]

The difficulty of assessing bomb damage in such a radioactive environment would lessen the utility of radiation-based weapons. Currently defined military requirements for agent-defeat

[34] Used against an underground bunker, agents beyond the fireball are unlikely to be expelled into the atmosphere, mitigating the fact that they are not neutralized. In contrast, used against an aboveground facility, there is a significant chance that agents beyond the fireball will be released without being neutralized.

[35] It would be nearly impossible to fuse a weapon to detonate at the facility's center without very precise knowledge of the facility's geometry.

[36] If the radioactive products produced by a 10-ton nuclear weapon were spread over a radius twice as large as its destructive radius, those entering the fallout area one day after the detonation would receive a fatal dose of radiation in less than five minutes. But due to the natural decay of the radioactive fallout, after two weeks, people could remain in the same facility for an hour without getting radiation sickness, and, after six months, they could remain there for several days before getting a fatal dose of radiation. Such a capability is likely insufficient to effectively deny enemy use of a critical facility.

[37] Whether these weapons would be considered "nuclear" weapons is an issue of debate.

[38] This assumes no decontamination. One might argue that the enemy could vacuum the cobalt powder and reuse it against Americans.

weapons require that U.S. forces be able to assess the extent of facility destruction or denial. The same radioactivity that would deny a facility to the enemy might also prohibit American forces from thoroughly assessing damage, although robots might be used. In contrast, even a failed non-radiological agent-defeat mission would not prevent troops from entering the target facility if they were wearing chemical and biological protective gear.

Non-Nuclear Weapons

Non-nuclear agent-defeat approaches are categorized either as chemical neutralization or as high-temperature neutralization; the two can also be combined.[39] Non-nuclear weapons have the advantage of being able to separately tailor blast and agent-defeat effects. In theory, then, they can increase their agent-defeat capability without an accompanying massive blast that would break open the target facility and release chemical and biological agents. In contrast, increasing the fireball radius of a nuclear weapon necessitates increasing the blast radius.

Non-nuclear approaches to agent defeat require that the chemical or biological agents be broken out of their storage vessels to be neutralized. Doing this without collapsing the target bunker requires explosive fills that either spread piercing fragments or use small submunitions to rupture agent containers and munitions, without producing a massive blast. The U.S. military is currently developing such low-blast–high-fragmentation warheads.

Also common to many agent-defeat techniques is use of quickly expanding foam to seal the entrance hole made by the penetrating munition. While this may not prevent all chemical or biological agents from escaping during the initial blast (the physics of foams prevents them from expanding quickly enough to do this[40]), it will help block the escape after the blast of noxious agents not neutralized by the agent-defeat weapon.

Once chemical or biological agents have been broken out of their containers, a variety of defeat methods may be applied. Long-burning incendiary weapons are perhaps the most promising technology for agent defeat. Application of these against biological agents should be straightforward, as even the hardiest, such as anthrax, are destroyed by a few seconds' exposure to 140 degree Celsius heat. Chemical agents require substantially higher temperatures, possibly upward of 1,000 degrees Celsius for several seconds.[41]

Neutralizing chemicals may also be used for agent defeat, though they are likely only to be effective against biological agents. (Specially tailored weapons might neutralize specific chemical agents, but would probably require too much knowledge of a facility's contents to be operationally useful.) One simple example of this approach is the use of highly concentrated bleach. Weapons developers report that concentrated bleach can achieve a one-to-one ratio of biological agents killed to bleach used.[42] Tons of biological agent could be killed in a single attack, and more advanced chemicals might be even more efficient.

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39 Annex F, Common Solution/Concept List, Airforce Mission Area Plan. Available at: http://www.fas.org/man/dod-101/usaf/docs/mast/annex_f/part26.htm.

40 Thomas Ricks, "U.S. Military Considers Weapons That Disable Bunkers, Spare People," *Wall Street Journal* (July 1, 1999).

41 Ricks, "U.S. Military Considers Weapons That Disable Bunkers, Spare People."

42 Ricks, "U.S. Military Considers Weapons That Disable Bunkers, Spare People."

The primary limitation on incendiary and neutralizing chemical weapons is that they are effective only against exposed agents. Thus, the fragmentation stage of the weapon must rupture a given container to allow the follow-on fill—incendiary or chemical—to be effective. It will be difficult to do this if containers are massive or heavily shielded. However, in some facilities, radii of destruction and agent neutralization can be larger than those of small nuclear weapons.

Sophisticated weapons concepts can further reduce the potential for dispersion of live chemical or biological agents contained in a facility. One concept the Defense Threat Reduction Agency, the Office of Naval Research, and Lockheed Martin[43] are pursuing involves a high-temperature incendiary to be spread and ignited before, rather than after, the weapon's blast. When the facility temperature reaches 230 degrees Celsius, submunitions rupture the storage tanks, exposing the agents to the neutralizing heat. In addition, as a by-product of the heating reaction, chlorine and fluorine gases and hydrochloric and hydrofluoric acids, are created, further aiding in the neutralization of remaining biological agents.

Wearing mission oriented protective posture (MOPP) gear will protect friendly troops from live chemical and biological agents accidentally released during an attack on a storage or production facility, in contrast with the troops' vulnerability to radioactive fallout. An experienced MOPP user can suit up in less than 10 minutes, and MOPP gear can be worn for extended periods, though in hot weather this will impede performance. An uncontaminated suit can be worn for 30 days, but once a suit has become contaminated it must be changed or decontaminated within 24 hours.

CASE STUDIES

We now examine three situations involving underground targets, which American forces could confront in the future. We do not restrict ourselves to existing weapons, but rather explore which potential weapons might be useful. We do not consider nonmilitary means of dealing with the threat although these may be available. In each case, it is left to the reader to decide which option would be best.

Case 1—Libyan Chemical Weapons Complex at Tarhunah

In a recent article in *Jane's Intelligence Review,* Geoffrey Forden described the Tarhunah Chemical Weapons Complex (Figure 9):[44]

> In the mid-1990s, the USA alleged that Libya had constructed an underground nerve-agent production plant, buried under at least 18m of earth, 60km southeast of Tripoli. The main difficulty with attacking this facility would not be its depth, which appears well within the reach of even sub-kiloton weapons, but uncertainty about its underground location. Publicly available details about this plant are sketchy, but it appears that there are twin entrance tunnels, between 60m and 140m long. According to eyewitness accounts, both tunnels go around a large rock formation near their entrance, purportedly to defeat cruise missile attacks. However, it is not clear if they continue on in the same direction or make a

43 "U.S. DoD Expedites Anti Chem-Bio Weapons Development," *Jane's Defense Weekly* (September 18, 2002). Online at www.janes.com/press/pc020913_1.shtml.

44 Forden, "USA Looks at Nuclear Role in Bunker Busting."

sharp turn after passing this rock. After all, it is hard for an inexperienced observer to keep track of directions passing through tunnels. If the tunnels took up to a 60º turn around the rock formation, the main facility might be anywhere inside a roughly rectangular area 80m wide by 240m long.

Figure 9: Tarhunah Chemical Complex

The exterior of the complex was drawn by a Defense Department artist. While the three tunnel entrances are clearly visible, the exact location of the underground facility is unknown.

Forden argues that a 5-kiloton ground-penetrating nuclear weapon could be used to destroy the facility. He notes one caveat: "Other geologic formations in the area could significantly reduce the effectiveness of such a nuclear weapon. For instance, deep crevasses, if they lay between the explosion and the underground facility, would effectively neutralize the destructive power of the bomb."

Another factor weighing against using nuclear weapons to destroy this facility would be the fallout produced. The precise nature of the fallout would depend on whether the weapon were detonated inside the facility or in the surrounding earth, but to be conservative, military planners would have to assume the latter. Based on our calculations, this would result in 100 percent lethality over approximately 15 square kilometers. Though this zone would not reach Tripoli, concerns about fallout would require medical monitoring for civilians as far as 20 kilometers downwind from the blast.[45] If American troops were in this area, they would have to halt operations or risk being exposed to fallout. Troops could not enter the immediate facility area to inspect damage or collect intelligence, even with protective gear.

Many non-nuclear approaches might also be used to destroy or neutralize the complex:

- A single earth-penetrating conventional bomb could reach the facility if the target's location were precisely known. If the facility were operating, seismic sensing methods might detect the location of active machinery. An earth-penetrating missile the length of the current GBU-28 penetrator, modified to impact the earth at twice the GBU-28's current impact speed, could penetrate the 18-meter cover of soft rock and reinforced concrete and destroy the facility using conventional explosives.[46]
- If the facility cannot be precisely localized (and this seems likely), several penetrator missiles used simultaneously could mimic the effect of a small nuclear weapon. Extending the small diameter bomb concept to missiles the length of the GBU-28 would allow simultaneous

45 We use a threshold dose of 25 rem for medical monitoring.

46 Nelson ("Low-Yield Earth Penetrating Nuclear Weapons") calculates a maximum penetration depth of four times penetrator length in reinforced concrete at maximum impact speed. Penetration depth will be slightly larger in soft rock such as limestone.

delivery of as many as 24 penetrating missiles; several would be expected to penetrate the facility. Alternatively, multiple sorties could cover the entire suspected facility area.

- If it were determined that no available bombs could penetrate the facility, cruise missiles could be used to temporarily block its entrances. This would require periodic attacks to keep personnel and equipment out of the facility for an extended period.
- A no-personnel or no-vehicle zone could be established around the facility. A range of American intelligence assets would be trained on a designated area surrounding the complex, and any attempt to move material to or from the facility would be stopped. While the facility itself might continue to produce weapons, those weapons could not be removed and used on the battlefield.
- If the facility were operating, conventional electromagnetic pulse weapons might be applied to destroy or disable equipment inside. Because the pulse can easily travel down a bunker's power and ventilation ducts, equipment inside would be vulnerable to attack. Such a weapon could be delivered by cruise missile.

In each case of applying conventional weapons, collateral damage due to chemical dispersal would be minimal outside the facility. Inside, chemical agents would be dispersed, but U.S. troops inspecting the area could mitigate the dangers from these by wearing protective gear.

Case 2—Iraqi Surface Bunker Containing Anthrax

Iraq is suspected of retaining stockpiles of weaponized anthrax and is known to use hardened bunkers extensively. Here, we consider a hypothetical cut-and-cover bunker built with 5-meter-thick walls and a roof of reinforced concrete, buried under an additional 5 meters of earth (similar to that in Figure 5). The facility, 5 kilometers south of Baghdad, covers an area measuring 400 square meters and is 20 meters high. Built during the absence of United Nations weapons inspections, the bunker's existence became known to American intelligence through satellite imagery captured during its construction. It is believed to contain several tons of anthrax in storage barrels, though, in the absence of a continuing ground presence, this cannot be confirmed.

Early in a campaign against Iraq, military planners ask whether it would be possible to destroy the bunker's contents. A review of available penetrating weapons shows that conventional weapons can easily breach the facility, but military and political leaders are concerned that an attack would simply spread anthrax about the countryside. They ask for a review of options that would minimize collateral damage, and are presented with the following:

- If it were developed, a 20-ton penetrating nuclear weapon, detonated at the floor of the facility, could incinerate the bunker's contents, preventing the dispersal of anthrax. It would, however, spread nuclear fallout. Deaths from acute radiation poisoning would be expected as far as 1 kilometer downwind. People nearer than 4 kilometers downwind would, if they were not evacuated quickly, receive a radiation dose greater than that received by a nuclear worker over a single year.
- If the stress of bomb impact caused the nuclear weapon to malfunction, the conventional explosives might detonate, but with no nuclear yield and, although unlikely, anthrax could be

dispersed from the bunker without being neutralized. Alternatively, the nuclear bomb might detonate, but at its "natural" yield of 10 kilotons, in which case radioactive fallout would then kill people as far downwind as 30 kilometers, perhaps including many in Baghdad.

- A penetrating bomb carrying a fragmenting warhead and incendiary materials could be used. The fragmenting warhead would break the anthrax out of exposed containers, and the heat from the incendiary materials would neutralize the anthrax. If containers were heavily shielded, they would not break open and, while the anthrax would not be destroyed, neither would it be released. The bunker would remain intact.
- A penetrating bomb carrying submunitions and neutralizing chemicals could be used. The submunitions would spread throughout the bunker and break the anthrax out of its containers, even if it were stored behind barriers, but the neutralizing chemicals would render the anthrax inert. The bunker would probably remain intact, but it could be breached if it had been poorly constructed.
- A watch could be placed on the facility using satellite imagery coupled with armed unmanned aerial vehicles. Anything attempting to enter or leave the bunker would be destroyed, making the anthrax inside unusable.

Case 3—North Korean Nuclear Weapons Complex at Kumchangri

In a recent Congressional Research Service report, Larry Niksch describes the North Korean Kumchangri underground complex, built in the side of a mountain:[47]

> U.S. intelligence agencies reportedly became aware of the Kumchangri underground facility in the second half of 1996. The Defense Intelligence Agency (DIA) reportedly prepared a classified report at the end of 1997, which concluded that the facility, located about 25 miles north of Yongbyon [50 kilometers north of Pyongyang], "possibly could be a nuclear weapons-related facility by 2003." The report stated that: "The function of this site has not been determined, but it could be intended as a nuclear production and/or storage site." . . . The Clinton Administration responded to the disclosure by pressuring North Korea to allow the United States access to the Kumchangri facility. An agreement was reached on March 16, 1999, providing for multiple inspections of the site in return for at least 500,000 tons of new U.S. food aid for North Korea. The first visit took place in May 1999, a second in May 2000. Administration officials declared that no evidence of nuclear activity was found. However, previous reports indicated that North Korea had removed equipment from the facility.

Had the United States or North Korea rejected a diplomatic solution, and had the United States concluded that the facility was being used to build nuclear weapons, what military choices would have been available for destruction or neutralization of the facility?

The depth of the facility is not publicly known, but given it is tunneled into the side of a mountain, the main facility could quite possibly be deeper than 200 meters, putting it out of the range of even megaton-sized, earth-penetrating nuclear weapons. Even if the facility were only 150 meters underground, a 1-megaton penetrating nuclear weapon would be required to destroy it, and the resulting nuclear fallout would have enormous consequences:

[47] Larry Niksch, *North Korea's Nuclear Weapons Program* (Washington, D.C.: Congressional Research Service, 2002).

- If the wind were blowing southwest, residents of Pyongyang, 80 miles away, would have to be evacuated within hours of detonation to prevent the death of more than 50 percent from radiation poisoning.
- If the wind were blowing north or northwest, residents of several large cities in China would have to be evacuated within hours of detonation to avoid numerous radiation deaths.
- If the wind were blowing south, residents of several large cities in South Korea would have to be evacuated within hours of detonation to avoid numerous radiation deaths, and U.S. troops stationed in the DMZ would have to be evacuated.

These consequences would almost certainly deter any U.S. leader from launching such an attack. Instead, military planners might seek to disable, rather than to destroy, the facility. The following options might be considered:

- A nuclear weapon might be used to deposit radioactive contamination at the entrances to the complex and thus to isolate the facility. However, a weapon small enough not to entail fallout problems would be unlikely to keep workers out of the facility for more than a period of weeks, especially since workers would be exposed only when outside the facility—once inside, the surrounding rock would shield them from radiation.
- Cruise missiles could be used to collapse entrances to the bunker. The entrances might be reopened quickly, and as with radiological area denial, the effect would likely be brief.
- Thermobaric weapons could be used to send high-pressure shock waves down the tunnels, possibly destroying equipment inside the facility.

Again, these options are unlikely to be satisfactory. If a military solution were still desired, the information-umbrella–type approach could be applied. The United States, possibly together with allies, would declare that no North Korean vehicles would be allowed to come near the facility, and would use land mines and train surveillance assets in the Kumchangri area to monitor this curfew. Any vehicle attempting to enter or leave the facility would be destroyed.

CONCLUSIONS AND RECOMMENDATIONS

Advances in non-nuclear weapons can produce many of the capabilities heretofore possible only with nuclear bombs. Yet our current non-nuclear capabilities often fall short, and may continue to without changes in our approach to weapons development. To help address these shortfalls, we offer the following recommendations:

Recommendation #1—Stress Intelligence

An approach that focuses simply on maximizing the penetration ability and explosive power of our weapons is unlikely to succeed against the most challenging targets—even the most powerful nuclear weapons cannot destroy bunkers tunneled under just 400 meters of granite. A focus on intelligence, particularly in identifying targets and localizing their entrances, will be more difficult to counter. If an enemy with a 100-meter-deep facility finds it threatened by a 1-megaton nuclear weapon, it can counter simply by digging 100 meters deeper, which will render the nuclear weapon ineffective. But if the facility's entrances can be identified, digging the actual bunker 100 meters deeper will have no effect on a strategy of closing entrances.

Recommendation #2—Use Air Supremacy

A large part of the rationale for an opponent's use of asymmetric capabilities—chemical and biological weapons, and HDBT—is that the dominance of American airpower makes aboveground conventional targets excessively vulnerable. Thus when developing approaches to defeating chemical and biological weapons and HDBT, we should take full advantage of American airpower dominance. Since the target set is not numerous and not mobile, high-capacity delivery vehicles—like B-2, B-1B, and B-52 bombers—need not be discounted in favor of smaller and cheaper vehicles—like F-16 or F-18 fighters. We should also relax the requirement that a new weapon be able to complete target destruction in a single pass because we are very likely to be able to penetrate enemy airspace repeatedly. Thus, while a nuclear bomb can provide maximum destruction in a single pass, multiple conventional bombs, delivered in a sequence of sorties, may produce a similar effect. Airpower dominance also allows us to rely on special operations forces, which, under the protection of American airpower, might operate deep within enemy territory to conduct sustained and accurate destruction operations.

Recommendation #3—Focus on Biological Agents

In setting out the requirements for its agent-defeat warhead, the Air Force announced:[48] "The goal of the Agent Defeat Warhead Program will be to demonstrate that the warhead is effective against both chemical and biological agents, and related hardware and/or munitions. . . ." This means that a single payload would have to destroy both chemical and biological agents. Yet those engaged in the agent-defeat program at Eglin Air Force Base spent 10 years on the agent-defeat program and have found no solution that would neutralize both chemical and biological agents. Our analysis shows that this conclusion should be no surprise—chemical agents are much more difficult to destroy than biological agents.

Thus, there seems to have been a recent shift in attitudes: In describing the Pentagon's new Agent Defeat Warhead ACTD, Air Force Lt. Col. John Wilcox noted, "We're looking at a variety of fills that we would go against different chemicals and different bio-agents with."[49] This change means, for example, that a payload highly effective against biological weapons, but ineffective against chemical agents, might be pursued. Such an approach should extend throughout the Department of Defense's agent-defeat efforts. Because chemical agents are much more difficult to destroy than biological agents, the requirement for a universal weapon undermines the pursuit of approaches that might succeed against biological agents. In addition, neutralization of biological agents should be a much higher priority than neutralization of chemical weapons, since the potential for collateral damage from dispersal of chemical weapons is much lower than that from biological weapons.

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[48] Program Research and Development Announcement. (Air Force Research Laboratory, Munitions Directorate, Ordnance Division). Online at www.fas.org/man/dod-101/sys/smart/docs/Adwprda.htm.

[49] DOD briefing on 2002 Advanced Concept Technology Demonstrations (March 5, 2002). Online at www.defenselink.mil/news/Mar2002/t03052002_t0305sp.html.

Recommendation #4—Evaluate Weapons in Context

Compared simply by destructive power, nuclear bombs surpass non-nuclear weapons every time. Yet weapons are useful only insofar as they can be integrated into operational plans and battlefield strategies. While conventional weapons are tested in war games and validated with military chiefs, nuclear weapons often are not. Thus, we pursue nuclear weapons, such as the 1.2-megaton Robust Nuclear Earth Penetrator, that no military commander would likely ever choose to use.

The valuable taboo against the use of nuclear weapons perversely shields these weapons from the same examination during their development that all other weapons receive. This may lead us to pursue militarily unattractive nuclear weapons developments. If civilian leaders decide to consider pursuit of new nuclear weapons, uniformed military must subject these weapons concepts to the same scrutiny they apply to other weapons systems.

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