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Nuclear "Bunker Busters" Would More Likely Disperse Than Destroy Buried Stockpiles of Biological and Chemical Agents

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Using nuclear earth penetrators to attack hardened storage bunkers containing stockpiles of chemical or biological (CB) weapons would probably fail to kill or neutralize the agents. The explosion is more likely to disperse active CB agents into the environment, potentially adding to the casualties already expected from the intense radioactive fallout.

The direct nuclear radiation and heat from a shallow-buried nuclear explosion is initially absorbed by the dense rock or dirt near the warhead, vaporizing and melting rock out to a radius $R \approx 5W^{1/3}$m for an explosion of yield W kilotons. A strong seismic shock crushes rock to a distance approximately 10 times larger, $R_S \approx 50W^{1/3}$m. The expanding cavity of hot gasses, acting like a piston, then ejects this crushed material without significantly heating it. Simple energy constraints show that only a small fraction of the crater material originating close to the explosion can reach the high temperatures and radiation levels needed to destroy CB agents. Agent munitions located outside of the small sterilization zone, but within the final crater volume, would be ruptured by the shock and ejected along with the radioactive fallout.

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A more sensible strategy would be to use conventional means to seal all entrances and exits to the facility and keep them sealed until the territory could be captured and the agents carefully neutralized.

INTRODUCTION

The United States military is increasingly concerned with the proliferation of deeply buried and hardened bunkers that cannot be destroyed with conventional weapons, especially those that may be used to store chemical and biological agents (CBW).[1,2] The recent *Nuclear Posture Review* (NPR) states that as of 1998 "approximately 1100 [underground facilities] were known or suspected strategic [weapons of mass destruction], ballistic missile basing, leadership or top echelon command and control sites."[3]

Underground structures protected by more than about 10 meters of hardened concrete cannot be destroyed with conventional earth penetrating "bunker-busters," such as the GBU-28 first used during the 1991 Gulf War. As shown in an earlier article, a penetrator made of the strongest materials cannot burrow into concrete or rock deeper than about 10–20 meters without crushing itself due to the extreme material stresses at impact.[4]

Even if a bunker were buried at a relatively shallow depth, however, it would be dangerous to attack a suspected CBW storage site with a conventional high explosive. Although the blast and shock may be sufficient to fracture reinforced concrete, collapse support structures, rip out communication lines, internal plumbing and ventilation shafts and destroy heavy machinery, the chemical or biological agents will remain toxic unless exposed to high temperatures or neutralizing chemicals for a sufficient length of time. In fact, active chemical and biological agents would more likely be dispersed than destroyed in the process. Although the gas products from a chemical detonation reach temperatures of several thousand degrees centigrade, the temperature spike lasts only a few seconds, too short to sterilize full canisters of CBW—a fact that should be clear to those who have quickly passed their fingers through a candle flame.[5]

There is also a danger that blowing up a bunker filled with chemical or biological material will vent and disperse active agents into the environment, possibly infecting civilians or military personnel down wind. Concern over reported cases of "Gulf War syndrome" led the Department of Defense to consider whether the illness was caused by release of Sarin gas following the demolition with conventional bombs of a storage bunker at Khamisi-yah Iraq.[6] A warhead with one ton of high explosive produces peak overpressures in excess of

100 kilobars and expansion velocities that can exceed 8000 m/s.[7] The pressure impulse is sufficient to eject a crater of rock material about five meters in radius. However, the explosion can also disperse chemical agents into the atmosphere. Indeed, as Steve Younger, the civilian director of the Defense Threat Reduction Agency (DTRA) has said,

> In some cases you may not want to have an explosion because the explosion may have the unwanted effect of spreading the material around the countryside, not only having negative collateral damage effects, but also complicating the situation when our ground troops go in . . . It's not as simple as blowing it up.[8]

For this reason, the DTRA and the U.S. Navy have initiated an Agent Defeat Warhead (ADW) demonstration program to develop a kinetic penetrating weapon combined with a low-pressure incendiary warhead.[9] The weapon would penetrate to the interior of a buried facility and then ignite a "thermo-corrosive" filling that can maintain high temperatures in excess of 2000°F for several minutes without venting the contents to the environment. The HTI-J1000, for example, combines high-temperature explosives to ignite and burn chemical agents, with disinfectant chlorine and acids to neutralize biological agents.[10]

Recently, the Republican leadership in Congress, the Department of Defense and leaders of America's nuclear weapons laboratories have urged that the United States develop a new generation of earth penetrating nuclear weapons—nuclear bunker busters—that could be used to destroy hardened and deeply buried targets, especially those containing stockpiles of biological and chemical weapons. Editorials have described nuclear earth penetrators as the "ultimate germicide," arguing that the heat from the explosion would atomize the agents.[11] This was stated more formally in the Report to Congress on the Defeat of Hard and Deeply Buried Targets,

> Nuclear weapons have a unique ability to destroy both agent containers and CBW agents. *Lethality is optimized if the fireball is proximate to the target. This requires high accuracy*; for buried targets, it also may require a penetrating weapon system. Given improved accuracy and the ability to penetrate the material layers overlying a facility, it is possible to employ a much lower-yield weapon to achieve the needed neutralization.[12] [emphasis added]

As was shown in an earlier article, it is not possible for an earth penetrator to burrow deep enough to contain a nuclear explosion. The explosion would blow out a crater of radioactive dirt sufficient to contaminate the surrounding area with lethal levels of radioactivity (a few km radius for a 1 kiloton explosion).[13]

Less well understood, however, is that even a nuclear-armed earth penetrator would be unlikely to destroy buried stockpiles of chemical or biological agents. Despite the extremely high temperatures and radiation levels reached very near a nuclear explosion, the destruction of buried biological or chemical agents would only be assured if the warhead detonated very close to the actual containers.

Essentially, the weapon would have to penetrate inside the bunker and detonate nearly in the same underground room in which canisters of biological or chemical (CB) agents were stored—a highly unlikely event given that in most cases the bunker geometry would not be known with any precision. It would be unlikely in any case that all CB agents in an underground complex would be stored within a single room. The size of the ejected crater produced would be much larger, however, and would result in the venting and dispersal into the atmosphere of any undestroyed CB material inside the crater zone.

Simply blowing up a bunker filled with chemical or biological agents—even using a nuclear weapon—may thus have the undesirable effect of dispersing the agents, rather than destroying them. If dangerous material were already stored deep underground, the most sensible strategy would be to make sure it stays there using conventional means to seal all entrances and exits to the facility and keep them sealed until the territory can be captured and the agents carefully neutralized.

SOME SIMPLE ESTIMATES

The physics of underground nuclear explosions is described in more detail below, but the primary conclusion is easy to understand from a simple back-of-the-envelope estimate. The energy released in a nuclear explosion of yield W kilotons (TNT equivalent) is

$$E = 10^{12}W \text{ calories} = 4.2 \times 10^{12}W \text{ Joules.} \tag{1}$$

Because the mass density of soil or rock is several thousand times larger than air,

$$\frac{\rho_{\text{ground}}}{\rho_{\text{air}}} \approx 2000, \tag{2}$$

the high temperatures and prompt radiation that one normally associates with nuclear explosions have a much shorter range in a buried explosion. Indeed, even if the weapon were detonated underwater, and all of its energy used just to generate steam at 100°C, the explosion would only be able to vaporize a cavity of radius

$$R_{\text{water}} = \left(\frac{3E}{4\pi\rho Q_v}\right)^{1/3} = 7.3W^{1/3}\,\text{meters}, \tag{3}$$

where $Q_v = 2.6 \times 10^6$ J/kg is the heat of vaporization of water and $\rho = 10^3$ kg/m^3 is the density of water. Clearly, an underground explosion would vaporize an even smaller cavity of rock. The example of water vaporization is not just hypothetical, since most rocks and soil contain substantial quantities of water. As vaporized rock and soil recondense, much of the remaining gas vented from the crater is superheated steam.

The size of the crater produced depends on the depth of the explosion and the water content of the soil or rock. As can be seen from Figure 1, the crater volume is typically $V \approx 10^5 W\text{m}^3$, corresponding to an apparent crater radius of approximately $R \approx 50W^{1/3}$ m and an ejected mass of about $M = 2 \times 10^{11} W\text{gm}$.[14,15] If all of the energy released were available to heat the ejected material evenly, the mean energy gained per unit mass would be about

$$\left\langle \frac{E}{M} \right\rangle \approx 21\,\text{kJ/kg}. \tag{4}$$

This would be sufficient to raise the ejecta temperature by only about 5–20 degrees, depending on the rock type and the water content.

Of course, the heat from the explosion is *not* uniformly distributed and is mainly confined to a small cavity of vaporized rock and steam, which expands and vents to the atmosphere. Equation (4) merely indicates that most of the ejected material is never brought to high temperatures—including any CB agents that lie outside of the initial vaporized volume of material. Note that this conclusion is independent of the weapon yield, so that using a larger warhead does not increase the average heating—only the cavity radius.

Nuclear Radiation

Direct nuclear radiation from a nuclear explosion would also be insufficient to destroy buried stockpiles of CB agents shielded by more than a few meters of soil or rock. About 5 percent of the total energy released in a nuclear explosion is in prompt neutron and gamma radiation.[16] For sufficiently high

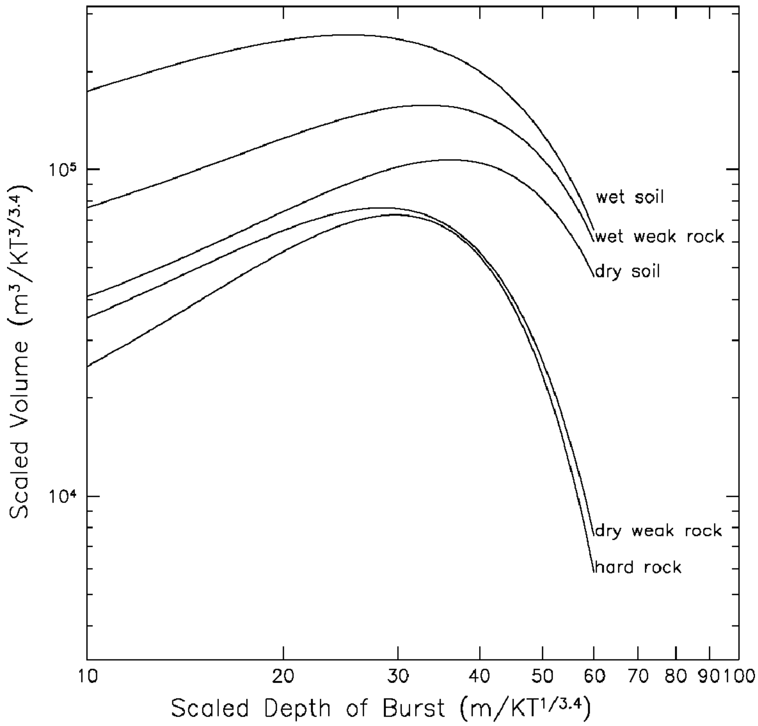

Figure 1: The scaled volume of the apparent crater produced by a buried nuclear explosion as a function of the scaled depth of burst $D/W^{1/3.4}$. The crater size is largest in wet soil or saturated rock due to the gas acceleration from high-pressure steam, and it peaks at scaled depths of 30–40 $m/W^{1/3.4}$. The apparent radius and depth are related to the apparent volume by $R_a = 1.2V_a^{1/3}$ and $D_a = 0.5V_a^{1/3}$. A 1-kiloton explosion detonated at a depth of 30 m would produce a crater of radius $R_a \approx 50$ m. Source: Northrop, J. A. (ed.), *Handbook of Nuclear Weapon Effects: Calculational Tools Abstracted from DSWAs Effects Manual One (EM-1)* (Defense Weapons Special Agency, Washington, D.C., 1996).

doses—of order one million rads (1 Mrad) or greater[17]—this radiation could destroy stored chemical and biological agents such as nerve gas and anthrax. The prompt neutron dose received by any unshielded agent from a point explosion is approximately[18]

$$D = 5 \times 10^{11} W \frac{e^{-k\rho R}}{R^2} \text{ rads,} \tag{5}$$

where R is the distance in meters, k is the mass attenuation coefficient and ρ is the density. For air, $k = 0.037$ cm^2/gm and $\rho \simeq 1.12 \times 10^{-3}$ gm/cm^3, so that

Table 1: The shielding length (cm) for direct nuclear radiation in various materials.

Material	**Fast neutron attenuation length (cm)**	**0.5 MeV gamma attenuation length (cm)**
Air	2.4×10^4	9×10^3
Water	9.7	10.3
Ordinary concrete	11	4.5
Soil	17	6.8

A few meters of water, soil or concrete will reduce the received neutron and gamma flux by several orders of magnitude. The fast neutron attenuation length in concrete and soil is approximate, and is sensitive to the water content of the medium.
Source: Glasstone, S., P. J. Dolan, U.S. Dept. of Defense, U.S. Dept. of Energy, & U.S. Defense Atomic Support Agency, *The Effects of Nuclear Weapons* (U.S. Dept. of Defense, (Washington), 1977).

$k\rho \simeq (240\ \mathrm{m})^{-1}$. Hence, the neutron flux in air is substantial for biological materials within a few hundred meters of the explosion. Not surprisingly, the direct neutron radiation from a nuclear explosion can destroy biological agents if they are stored above ground.[19]

In contrast, the density of rock is three orders of magnitude higher than that of air. For an earth-penetrating warhead that does not detonate inside the actual storage room, or very near it, the penetrating radiation will be absorbed by the intervening soil, rock, or concrete walls (see Table 1). Data from contained underground nuclear explosions indicate that nearly all of the radioactivity is contained in the glassy material lining the cavity with a thickness of about 25 cm.[20] Consequently, the direct nuclear radiation itself cannot destroy CB agents stored further than a few (scaled) meters from the point of detonation.

The following sections review, in more detail, the physical environment produced in an underground nuclear explosion and the conditions necessary to destroy chemical and biological agents. However, the simple estimates presented above already indicate that CB agents are unlikely to be destroyed by a nuclear explosion if they are shielded by more than about 5–10 Wm of dirt, rock or concrete.

SHALLOW BURIED NUCLEAR EXPLOSIONS

Figure 2[21] illustrates the sequence of events following the detonation of a shallow buried nuclear weapon:

First microsecond after the detonation. The nuclear fission or fusion is complete and the weapon itself has vaporized. The initial temperature and

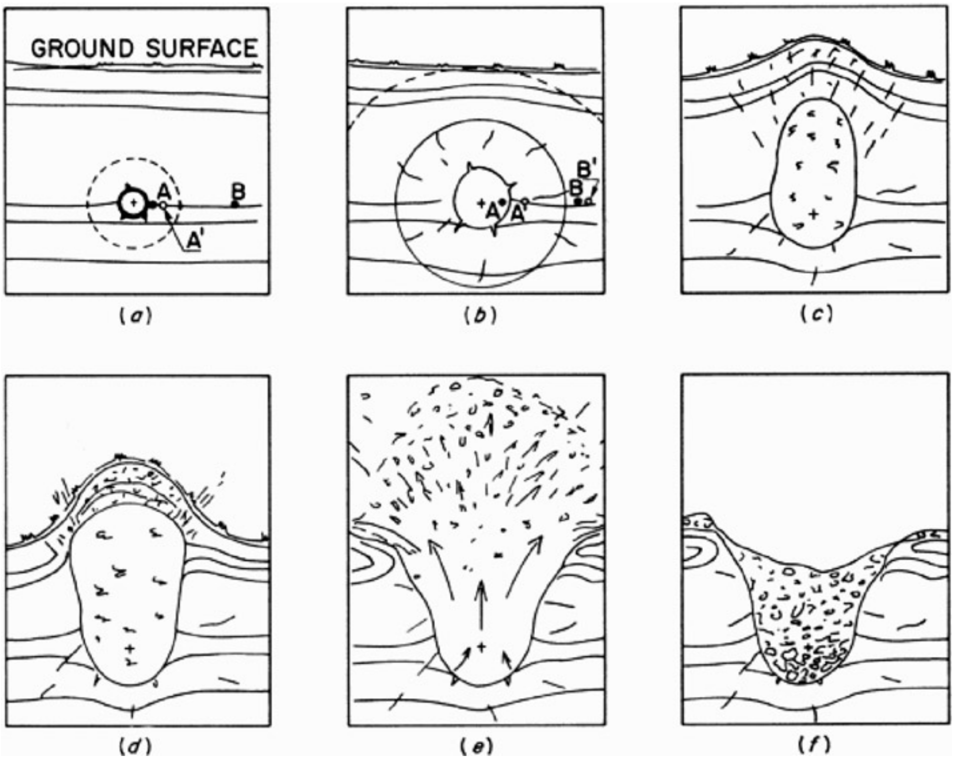

Figure 2: The sequence of events in a shallow-buried underground nuclear explosion. The nuclear detonation generates a strong shock wave that vaporizes a cavity of rock with initial radius $R \approx 2W^{1/3}$ m and melts rock out to twice this distance. There is little postshock heating beyond this radius, but the shock is sufficiently strong to crush rock out to approximately $R_a \approx 50W^{1/3}$. The cavity is filled with high pressure and high temperature gasses and expands outward. A combination of tensile spalling and gas acceleration drives out the crater ejecta. Source: Short, N. M., *The Definition of True Crater Dimensions by Post-Shot Drilling* (No. UCRL-7787): Lawrence Livermore National Laboratory (1964); Teller, E., *The Constructive Uses of Nuclear Explosives* (McGraw-Hill, New York, 1968).

pressure of the weapons material can exceed 10 million $^\circ$C and a million atmospheres in pressure.

Few milliseconds. An expanding shockwave first compresses the rock and then unloads. At pressures exceeding 1 Mbar[22] this process is thermodynamically irreversible, heating and vaporizing the rock out to a radius of about 2 $W^{1/3}$ m and melting it out to about $4W^{1/3}$ m. The gasses inside the resulting cavity have a temperature near the liquid-vapor equilibrium for rock (about 4000°C) and the pressure is many orders of magnitude greater than that from the overburden. The shock wave continues to propagate at roughly 5 meters per millisecond, outrunning the expanding cavity. Although the shock strength decreases with distance, it is strong enough to crush and fracture the rock out to a radius of about $50W^{1/3}$ m.

10–50 milliseconds. The compressive shock wave reaches the free surface and the energy of compression begins to be converted into kinetic energy. The resulting rarefaction wave upon reflection propagates downward, allowing the compressed rock to expand explosively, further breaking it up. If a bunker or tunnel is present within this fracture zone, it will be crushed along with its contents. The cavity expands, dropping in temperature and pressure. The vaporized rock will condense to a glassy melt, roughly 70 tons per kiloton yield, which contains most of the radioactive fission products of the explosion. The primary gas remaining is high-pressure superheated steam.

100–500 milliseconds. The cavity gas continues to expand pushing and accelerating previously crushed crater material outwards. The bulk of this material will be ejected mechanically by a piston-like motion forced by the high-pressure cavity gasses—but the material is never heated to the high temperatures inside the cavity. The cavity breaks the surface and vents its hot gases (mainly steam) to the atmosphere. The temperature of the vented gas does not exceed a few thousand degrees.

1–2 seconds. Pulverized rock is ejected from the crater. Nearly all of this material is unheated, but some hot glassy material from the central cavity is mixed in with the ejecta.

Radius of Vaporization and Melt

The maximum volume of rock that is vaporized in the first few milliseconds can be estimated by assuming all of the bomb energy is converted to the heat of vaporization,

$$V_v < \frac{E}{\rho Q_v} \approx 110W\mathrm{m}^3, \tag{6}$$

for a typical density and heat of vaporization for the rock [see Table 2]. This corresponds to a maximum radius of the vaporized cavity, $R_v < 3W^{1/3}$m. Likewise, assuming a specific heat of melting $Q_m = 1.8$mJ/kg, one finds a limit on melted volumes $V_m \leq 800W\mathrm{m}^3$ and $R_v \leq 6W^{1/3}$m. These are upper bounds, however, because not all of the energy goes into melting or vaporizing the rock. Nevertheless, these estimates are very close to a standard rule of thumb established from deep underground tests, $V_v \leq 70W\mathrm{m}^3$ and $V_m \approx 700W\mathrm{m}^3$.[23]

Table 2: Spherical radii of vaporization for a one kiloton explosion in six natural materials.

Material	Density (tones/m^3)	Vaporization energy (cal)	Vaporization pressure (Mbar)	Radius of vaporization (m)	Mass vaporized (tones)
Granite	2.67	2800	1.8	1.83	68.6
Saturated tuff	1.97	2800	1.11	2.06	72.1
Dry tuff	1.76	2800	0.865	2.15	73.2
Alluvium	1.6	2800	0.703	2.20	71.4
Salt	2.24	1185	0.920	2.25	106.9
Water	1.0	620	0.196	3.30	150.5

Source: Butkovich, T. R., in *Shock Metamorphism of Natural Materials* (eds. Bevan M. French & Nicholas M. Short) pp. 83–85 (Mono Book Corp., Goddard Space Flight Center, 1967).

Table 2 summarizes calculations by Butkovich[24] who determined the cavity mass and radius of vaporization for a one kiloton nuclear explosion in common geological materials. The typical radius of vaporization is approximately 2 meters.

Note that a one kiloton explosion in water creates a vaporized cavity of only 3.3 meters in radius—about one eighth the volume of vaporization estimated above. This is because not all of the energy from an actual detonation is converted to the heat of vaporization.

The Cavity Temperature

While the initial temperature of the fully fissioned weapon can reach millions of degrees a few microseconds after the explosion, once the vaporized cavity has formed the temperature cannot be much more than the vaporization temperature of rock—approximately 2500–4000°K—else additional rock material would continue to boil off. The pressure is very high and the cavity expands rapidly. For adiabatic expansion of an ideal gas PV^γ is constant, where $\gamma = c_p/c_v$ is the ratio of specific heats. For silicate rocks, evidently $\gamma = 4/3$ is an adequate approximation right up to the liquid-vapor phase boundary,[25] so that $P \propto R^{-4}$ and $T \propto R^{-1}$. However, the equation of state is more complex as the silicates and other refractory materials begin to condense, and latent heat is put back into the remaining gas. This leaves the volatiles, mainly carbon dioxide gas and superheated steam inside the cavity.

Data from the *contained* Ranier explosion indicates that the steam temperature was approximately $T_0 \approx 1500^\circ\text{C}$ when the cavity reached its maximum radius.

Outside of the cavity, the temperature decreased very rapidly. Figure 3 shows the temperature profile for the contained Ranier explosion at 90 ms after

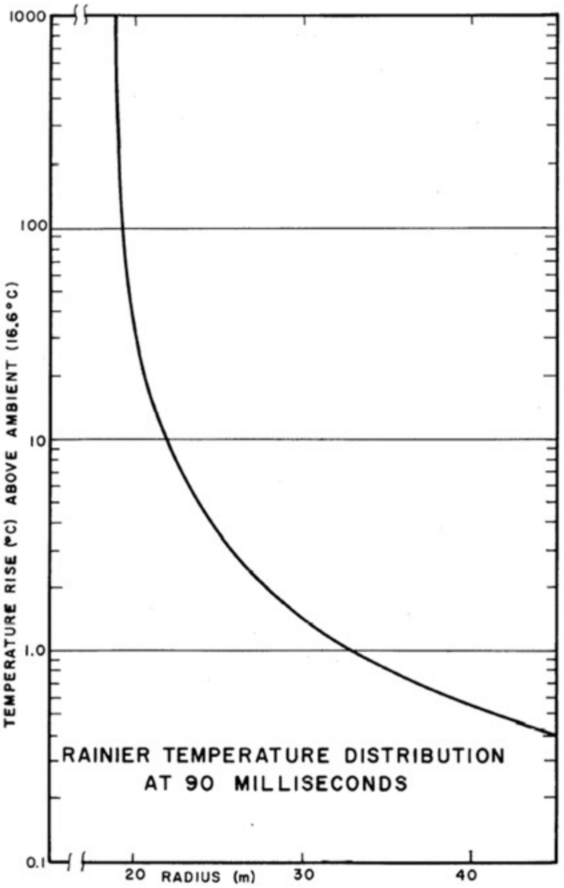

Figure 3: The simulated temperature distribution outside of the cavity of the 1.7 kiloton Rainier test at 90 milliseconds after the explosion. By this time, the initial ~3 m vaporized cavity has expanded to approximately 19 m in radius and the gasses have cooled to about 1500°C. Note there is little heating beyond 2 cavity radii. Source: Heckman, R. A., *Deposition of Thermal Energy by Nuclear Explosives* (No. Ucrl-7801): Lawrence Livermore National Laboratory. (1964). Available at http://www.llnl.gov/tid/lof/documents/pdf/19111.pdf (Accessed April 1, 2004).

detonation, when the cavity reached its maximum radius. Data from other fully contained explosions indicate that the temperature drops to that of the ambient medium temperature within 1–3 cavity radii.[26]

The temperature history of the vented gas for a cratering explosion will be more complex than if the explosion is contained. The primary mechanism for ejection of material out of the crater is through the work done by the expanding bubble of high temperature steam. As the steam diffuses through voids and cracks in the rubble, it will lose some heat to neighboring material, especially if the rock is saturated with water whose latent heat of vaporization is high.

Except for very shallow bursts, the temperature of the vented steam should not be greater than that of a fully contained explosion. That is, the vented gas should not be much greater than 1500°C. Thus, even ejecta that are briefly exposed to the hot vented gasses during the explosion will not sustain temperatures greater than 1500°C for more than a few seconds.

Ground Shock

Any containers or munitions filled with chemical or biological agents will be ruptured by the strong ground shock. Figure 4 shows the simulated peak radial stress as a function of the radius for a 5-kiloton contained explosion. The radii of vaporized and melted rock are approximately 3 and 6 meters, respectively, consistent with the previous estimates. These occur while the shock pressure exceeds 1.3 and 0.8 Mbar.

Rock begins to crack or fracture at pressures greater than about 0.5 kbar and is crushed at pressures exceeding 5 kbar—much less than the pressures required to melt or vaporize. Consequently, the radius of the fractured and ejected rock is very much larger than the cavity region with its very high temperatures.

Thus, a nuclear explosion within 50 $W^{1/3}$ m of the storage site is likely to eject containers of CBW agents. The containers will have been crushed by the expanding shock wave, but the agent material will not have been heated to high temperatures unless they are initially very close to the explosion.

The peak radial stress exceeds 5 kbar out to about 80 meters, sufficient to crush rock. The shock speed is about 5 km/s so it reaches this distance within 15 msec—much less than the expansion time of the cavity. Shocks of this strength will be sufficient to crush canisters of CBW. U.S. nerve gas storage tanks, for example, are designed to withstand external pressures of 25 bar.[27] Thus the agents will be released, mixed with the ejecta, and be advected with the rest of the main cloud and base surge, and ejected from the explosion.

DESTRUCTION OF DISPERSED AGENT BY HEAT

Despite the constraints described above, one might ask whether CB agents exposed to the high temperature vented gases, $T \approx 1500^\circ$C, might nevertheless

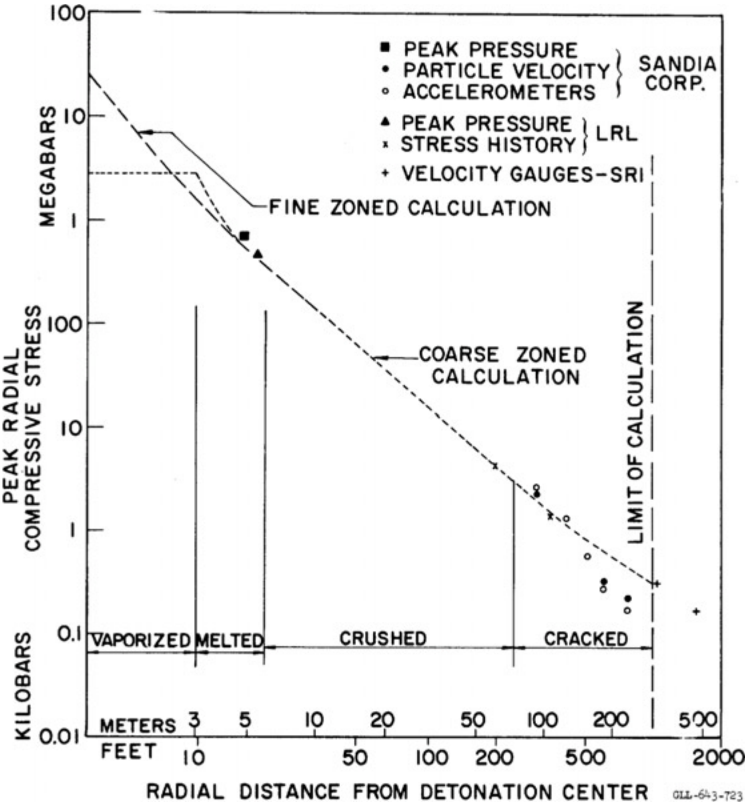

Figure 4: Peak radial stress in granite as a function of distance for a 5-kiloton nuclear explosion. The dashed line is the result of a numerical simulation and the open and filled points are from nuclear test data. Vaporization of granite occurs above 1.3 Mbar and melting occurs above 0.8 Mbar. Beyond the melting zone, at radii between 10–150 m, the rock is crushed but is not significantly heated. Source: Butkovich, T. R., *Calculation Of The Shock Wave From An Underground Nuclear Explosion In Granite* (No. Ucrl-7762 Reprint-1965-4-I): Lawrence Livermore National Laboratory. (1967). Available at http://www.llnl.gov/tid/lof/documents/pdf/19093.pdf (accessed April 1, 2004).

be destroyed. Here we demonstrate that this cannot be the case unless the CB agent is first dispersed in fine droplets less than a few millimeters in radius.

One can gain insight from the U.S. program to destroy its own CW stockpiles as required under the Chemical Weapons Convention (CWC).[28] Appendix A describes the incineration of chemical munitions at the Tooele Chemical Agent Disposal Facility in Utah. The Tooele facility uses a multistage incinerator operating at temperatures exceeding 1400°C. Even at these high temperatures, full canisters of chemical agent take more than 50 minutes to sterilize—primarily because the liquid agent must first boil off before it can reach temperatures exceeding its vaporization temperature. A faster process injects the agent into the furnace as an aerosol spray.

A shallow-buried underground nuclear detonation ejects most of the crater material on a time scale lasting a few seconds. Once the temperature in the cavity drops below a few thousand degrees, full canisters of CB agents—even very close to the cavity—will not have sufficient time to evaporate. However, the strong shock that precedes the cavity expansion may be sufficient to rupture the canisters and disperse the liquid agent.

Suppose that the agent was dispersed in small droplets of radius a just prior to being exposed to the high temperature gases of temperature T. The droplets will shrink in size as the outer layers evaporate, but during this time the droplet interior always remains below the vaporization temperature—373°K for water. The heat removed by evaporation is $\dot{m}Q$ where $\dot{m}$ is the mass loss rate and $Q = 2.2 \times 10^6$ J/kg is the heat of evaporation of water. This heat loss is balanced by the thermal heat of diffusion entering the droplet,

$$\dot{m}Q = 4\pi a^2 D \frac{dT}{dr}_{|a}, \tag{7}$$

where $D = 0.68$ J/s K m is the thermal conductivity of water. Writing the gradient, $dT/dr \approx T/a$ we find a characteristic time to evaporate the entire drop,

$$\tau \approx \frac{\rho a^2 Q}{3\alpha DT} = \left(\frac{a}{10^{-3}m}\right)^2 \left(\frac{1000^\circ \mathrm{K}}{T}\right) s \tag{8}$$

where $m = 4\pi a^3 \rho/3$ and $\rho = 10^3$ kg/m^3 is the density of water. Thus, droplets of size greater than a few millimeters should survive exposure to high temperatures of a few thousand degrees for a few seconds. They will not be heated beyond their boiling point, and will remain active and highly toxic agents.

SUMMARY AND CONCLUSIONS

Only agents stored close to the initial cavity radius, $R \approx 5W^{1/3}$ meters from the detonation point, are likely to be sterilized by a nuclear explosion. Material stored further away, but within the crater volume, will be ejected and mixed with the radioactive fallout without being neutralized.

A nuclear EPW would essentially have to detonate in the same underground room as the stored CBW to guarantee their destruction. However, it is highly unlikely that any earth-penetrating nuclear weapon could achieve the necessary accuracy and depth to detonate right inside the facility. As shown in an earlier article, no EPW can reach depths in excess of about 10–20 meters of hardened concrete without crushing itself in the process. Even if the bunker is shallow, however, the exact location and physical geometry of the facility will be highly uncertain.

In conclusion, the main points of this article can be summarized as follows:

- Destruction of CB agents requires radiation exposures exceeding 1Mrad or sustained high temperatures sufficient to vaporize and incinerate liquid agent. Data from U.S. chemical weapons destruction program indicates incineration of full munitions of chemical weapons can take more than 50 minutes at temperatures exceeding 1000°C.
- Direct neutron and gamma radiation from an underground nuclear explosion is absorbed within a few $W^{1/3}$ meters by intervening rock or soil.
- The expanding shock wave will heat material to temperatures sufficient to kill CBW only out to a radius of approximately $5W^{1/3}$ m.
- The shock will nevertheless, pulverize rock—and CBW canisters—out to a radius of $50W^{1/3}$ m. This material will be ejected from the crater.
- CB agents outside of the small destruction zone, but inside the crater, will be dispersed along with the crater ejecta without being sterilized.

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Appendix A: Incineration of Chemical and Biological Agents

As of 1997, the United States had approximately 30,000 tons of chemical weapons consisting of mustard gas, blister agents, and organo-phosphorus nerve agents. These chemicals have been weaponized in mines, rockets, artillery shells and bombs. Similar chemical munitions were found and destroyed by the United Nations Special Commission on Iraq inspections (UNSCOM) following the first Gulf war.[29]

The United States is destroying its chemical weapons stockpile primarily in high-temperature incinerators at eight separate sites in the continental U.S. and at the Johnston Atoll in the Pacific.[30] Figure A1 shows a pallet of 155 mm projectiles containing approximately 3 kg each of GB nerve agent (Sarin) at the Tooele Chemical Agent Disposal Facility in Utah. Prior to incineration, these projectiles are opened with remote cutting tools and the explosive burster removed. The liquid agent is either drained and then

Figure A1: Pallets of 155 mm projectiles each containing approximately 3 kg of GB nerve agent (Sarin) at the Tooele Chemical Agent Disposal Facility in Utah. The munitions are cast from high-strength steel. Prior to incineration, the projectiles are opened with remote cutting tools and the explosive burster removed. Even at incinerator temperatures exceeding 1000°C, full containers of GB require nearly an hour or more to completely vaporize and destroy the agent. The mechanism in the foreground is part of an experiment to develop a method of noninvasive agent identification using neutron spectroscopy. Source: Helmuth, L., *Seeing Through Steel: INEEL-Developed Technology Identifies Chemical Weapons*. Available at http://www.eurekalert.org/pub_releases/1998-10/INEE-STSI-141098.php (accessed April 1, 2004).

destroyed in a separate liquid incinerator, or boiled off directly from the full munitions.

Although many chemical agents will begin to decompose in the range of 100–300 degrees centigrade, complete destruction takes place much too slowly at these temperatures. For example, the half-life of GB at 300°C in aqueous solution is 146 hours.[31] The official U.S Army "5X" destruction criterion requires that the agent be vaporized and all metal parts of the munition be brought to a temperatures in excess of 1000°F (585°C) for at least 15 minutes.[32]

The Tooele disposal facility uses a multistage incinerator operating at temperatures exceeding 1400°C.[33] Figure A2 shows the temperature of the metal

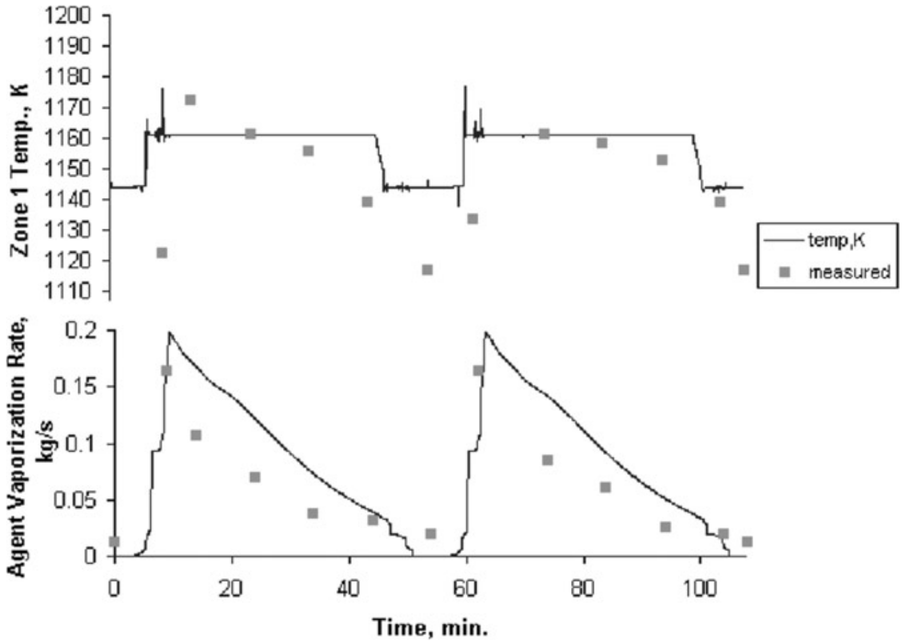

Figure A2: The temperature of the metal parts furnace and the agent vaporization rate from a pallet of twenty-four 105-mm projectiles filled with HD (mustard gas). Two cycles involving two different pallets of shells are shown. The curve is the result of a numerical simulation, while the solid data points are measured values. Each tray of projectiles is introduced from an airlock into the first zone where the majority of agent is driven off and combusted. The incinerator gas temperature is maintained near 1160°K with a residence time sufficient to drive off, destroy the agent, and bring the projectiles to at least 1000°F for at least 10 minutes. Note that complete vaporization and agent destruction at these temperatures can take nearly an hour or more. Source: Martin K. Denison et al., in 21st International Conference on Incineration and Thermal Treatment Technologies (New Orleans, Louisiana, 2002).

parts furnace and the agent vaporization rate from a pallet of 24 105 mm projectiles filled with HD (mustard gas). Each tray of projectiles is introduced from an airlock into the first zone where the majority of the agent is boiled off and combusted. The incinerator gas temperature is maintained near 1160°K with a residence time sufficient to boil away and destroy the agent.

The liquid agent within each projectile remains near, but always below, the boiling temperature, (258°C for mustard gas and 158°C for Sarin).[34] The agent is destroyed only after it has been vaporized. Thus, the time needed to sterilize full containers of chemical agent is essentially determined by the rate of vaporization, which in turn is determined by the rate of heat transfer between the hot furnace gasses and the liquid inside the projectiles or canisters.

In the example shown in Figure A2, complete vaporization of the full projectiles takes more than 50 minutes at temperature of 1170°K. Of course, the vaporization rate would increase at higher temperatures. However, the boiling heat transfer rate has a strong local maximum when the temperatures difference between the surface and the liquid is approximately 30°C. Only at extremely high temperatures differences—when radiation transfer begins to dominate—does the heat transfer rate exceed this local maximum.

Rapid evaporation would occur, of course, in the region very close to a detonating warhead. However, further away, the temperature will be much lower. As discussed above, the temperature of the vented steam from an underground nuclear explosion is about 1500°C—comparable to the temperature of the incinerators described here. Since a cratering explosion only lasts a few seconds, this is clearly not enough time to evaporate and destroy any ejected CB agents.

Appendix B: Comments on an Article by May and Haldeman

After completing most of the research on which this article is based, the author received a manuscript by Michael May and Zackary Haldeman[35] that also addresses the issue of agent defeat with nuclear weapons. They consider two cases: detonation inside a large bunker facility that is empty except for 1000 barrels containing 200 liters each of bioagents; and an underground detonation near, but outside, the structure. The first situation is highly unrealistic—as the authors acknowledge—given the likely absence of precise information on the bunker geometry and location, that CB containers and munitions may be spread over many rooms in a given complex and that no earth penetrating weapon can penetrate more than about 10–20 meters of hardened concrete. Not surprisingly, they conclude that CB materials within a few meters from a one-kiloton nuclear blast will be destroyed by the heat and radiation.

May and Haldeman are less certain when it comes to material stored beyond a few cavity radii away from a buried explosion—which I argue is the more realistic case. The issue hinges on the amount of heat transferred to the agents and their containers as the cavity expands and the superheated gasses diffuse through the crater material before venting. They do not attempt to calculate this case in detail, but state "there may not be enough time to heat the barrels that are not in the immediate vicinity of the explosion in the time available before venting." This leads to their somewhat more cautious conclusion that "for most likely cases complete sterilization cannot be guaranteed."

Although this article also does not calculate the detailed mixing and heat diffusion through the full venting, the simple estimates presented in the introduction show that there simply is not enough energy to sterilize chemical or biological agents if they are stored underground and more than about 5 $W^{1/3}$ meters from the explosion. One can thus conclude that for most likely cases the CB agents will not be sterilized.