Effectiveness of Nuclear Weapons against Buried Biological Agents

January 2004

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The authors are grateful to Lew Glenn, Hans Kruger, Michael Levi, Greg Mello, Rob Nelson, Milo Nordyke, Roger Speed, and Gary Stradling for insights and references. The authors are solely responsible for any mistake in this work.

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An abridged version of this article was published as May, M., Haldeman, Z., Effectiveness of Nuclear Weapons Against Buried Biological Agents. Science & Global Security, Vol. 12, 1-2: 91-114.

Effectiveness of Nuclear Weapons against Buried Biological Agents

Abstract

This report describes the results of some calculations on the effectiveness of penetrating nuclear weapons of yield 1 and 10 kilotons against targets containing biological agents. The effectiveness depends in detail on the construction of the bunkers, on how the bio-agents are stored, on the location of the explosions with respect to the bunkers, the bio-agent containers and the surface of the ground, and on the yield of the explosion and the geology of the explosion site. Completeness of sterilization of the bio-agents is crucial in determining effectiveness. For most likely cases, however, complete sterilization cannot be guaranteed. Better calculations and experiments on specific target types would improve the accuracy of such predictions for those targets, but significant uncertainties would remain regarding actual geology, actual target layouts, and the position of the explosion with respect to the target. Aboveground effects of the nuclear explosions, all of which would vent to the surface, include intense local radioactivity and significant fallout, air blast, and seismic effects to distances of kilometers. Based on preliminary calculations, however, casualties from those effects would be fewer than the casualties that would result from the dispersal of large quantities of bio-agents.

Introduction

This report describes the results of some calculations and estimates made regarding the use of penetrating nuclear weapons against targets containing biological agents. The use of nuclear weapons against such targets has been contemplated because conventional explosions that could destroy such targets might not, it is believed, deactivate the biological agents effectively but might instead release them, or some fraction, into the atmosphere. Nuclear explosions on the other hand, with their concomitant very high temperature and radiation field, are thought to be able to deactivate some or most of the agents.

The report is divided into three sections and a conclusion. The first section describes the phenomenology of underground nuclear explosions. Most of this phenomenology is based on data obtained by the U.S. Plowshare program on civilian uses of nuclear explosions in the 1960s and 70s. The second section describes the mechanisms by which a nuclear explosion can destroy bio-agents buried underground, in bunkers and otherwise. The effectiveness of the nuclear explosions depends in detail the construction of the bunkers; on how the bio-agents are stored; on the location of the explosions with respect to the bunkers, the bio-agent containers and the surface of the ground; and on the yield of the explosion and the geology of the explosion site. The penetration of projectiles into various geological sites is based on experiments and calculations carried out by the Sandia National Laboratories. The exposures to radiation and heat are based on calculations by Lawrence Livermore National Laboratory and our own estimates. The vulnerability of bio-agents is derived from various unclassified sources.

The third section presents the aboveground effects of the nuclear explosions considered, all of which would vent to the surface. These include local radioactivity, fallout, air blast, and seismic effects. These estimates are based on well-known nuclear weapons effects data and calculations. The conclusion brings together the main results and highlights certain policy consequences.

I. Phenomenology of Underground Nuclear Explosions

The rationale for using nuclear weapons against bio-agent targets is that the expected heat and radiation could deactivate the bio-agents and not just disperse them. This rationale applies to both surface and underground bio-agents targets. The case of surface bio-agent targets was treated, among others, by Hans Kruger[1] and will not be taken up further here. The rationale for using penetrating nuclear weapons against buried targets (bunkers) is that the heat and radiation will be communicated to the target more effectively if the nuclear explosion occurs in or as near as possible to the buried target. In this section, we summarize the complex phenomenology attendant upon nuclear explosions at two sample yields, 1 and 10 kilotons (kt) and at the attainable depths of burst (DOB) that might be expected for penetrating nuclear projectiles against buried bio-agents targets (from a few to 30 meters, depending on the type of material in which the targets are buried). We give scaling laws, usually in the form of diagrams, for other yields and DOBs insofar as possible.

The present knowledge of the phenomenology of underground nuclear explosions rests mainly on the results obtained in the series of experiments done in the U.S. Plowshare program in the 1960s and 70s,[2] and in the corresponding but larger program on civilian nuclear explosions carried out by the U.S.S.R. at about the same time. The calculations done since then have been normalized to those results. Results of new calculations undertaken in new geological areas and at different depths of burst can be considered valid at best to one significant figure, often only to a factor of two. This is in part because of the scarcity of and uncertainties in existing data, in part because of the complexity of the calculations needed for more accuracy, and in part because of the difficulty in adequately specifying key variables, such as the type of ground material.

We limit our description to cratering explosions (which vent to the surface and cause a crater) since the yields capable of heating or irradiating significant targets are large enough to crater at the depths that can be reached with penetrating projectiles. The phenomenology of cratering explosions has been described in several places.[3] A comprehensive summary of many data obtained in the Plowshare program is given in Teller et al., *The Constructive Uses of Nuclear Explosives*,[4] hereafter referenced in the text as Teller et al. General background facts mentioned here also can be found in that reference.

The energy of the nuclear explosive is released less than a microsecond after detonation,[5] creating initial temperatures on the order of 10 million kelvin and initial pressures on the order of a million atmospheres. The surrounding material (ground and structures) evaporates, ionizes, and begins to expand rapidly under the intense pressure. As a result, the explosion creates a cavity and sends a strong shock wave into the ground ahead of the cavity being formed. That shock initially is strong enough to fracture rock and any structure it encounters, weakening as it goes. For the yields discussed here, in a fraction of a second the shock weakens to an elastic wave over a few hundred meters, or over a shorter distance in an energy-absorbing material such as alluvium.

Within a few milliseconds of detonation, the temperature within the cavity drops below the vaporization temperature of the ground but remains above its melting point. The ratio of melted rock to vaporized rock is about 8:1 in contained explosions.[6] Melting is usually complete within a few tens of milliseconds at most, so this ratio likely holds also for explosions that will subsequently crater.

In the case of an explosion buried deeply enough to be contained, cavity growth stops when the cavity pressure equals the pressure of the overlying ground. For an explosion that will vent to the surface and create a crater, as is the case with penetrating projectiles, pressure balance does not occur before the shock reaches the surface. At that time, the ground surface spalls upward under the influence of the shock pressure and a rarefaction wave[7] moves into the ground from the ground surface toward the cavity. When the rarefaction wave reaches the expanding cavity, it fixes the horizontal cavity radius, so cavity growth becomes asymmetrical, predominantly upward, and slower than before. The cavity radius as used here is the radius of the lower half of the cavity due to vaporization, melting, and expansion under the pressure of the hot gases before the pressure is relieved by rarefaction. Immediately before venting, the cavity radius is between a few meters and a few tens of meters depending on the yield, depth of burial, and ground material. Distances and times at which given pressure and temperature occur are proportional to the yield to the 1/3 power at those early times. During the period of cavity formation in the geologies for which test data are available, the temperature is one thousand kelvin or more. Most of the energy of the explosion is retained in the cavity material up to that time.

The period immediately after the rarefaction wave returns is the gas acceleration phase. While the lower portion of the cavity is at its full size, the upward-expanding gases in the cavity give the soil above it an additional push. The pressure history during the gas acceleration phase, together with the depth of burial and the composition of the soil (particularly the amount of volatiles in it, such as water) determine the shape and size of the crater. Compaction and subsidence of the ground above the cavity may also contribute. In general, the width and depth of the crater follow a slightly different scaling law from the early-time scaling, closer to the 1/3.4 power.[8] Most of the material in the crater will fall back either into the crater itself or in the surrounding lip. The material may be compacted or fractured, depending on its original constitution, and will entrap most of the radioactivity and other material ejected (known as ejecta).

While these events flow into one another, each setting the initial conditions for the following ones, it is helpful for the purpose of the analysis to follow to keep in mind four fairly distinct time periods:

Period 1. Within a microsecond of the explosion, during which prompt gamma and neutron irradiation occurs within a few absorption mean free paths[9] of the explosion, and the thermal radiation from the explosion heats and evaporates the immediate surroundings. There is essentially no material motion during that period.

Period 2. From a few to a few hundred milliseconds after the explosion (depending on the DOB of the explosion and the nature of the ground), during which the explosion's high pressure creates the cavity, the radioactive fission products and other radioactivity mix with the vaporized material, and the shock compacts the ground and reaches the ground surface. Then a rarefaction wave returns to the cavity, which then grows only upwards, but there is little or no venting above ground yet.

Period 3. Following Period 2 and lasting up to a few seconds after the explosion, during which the underground cavity vents to the surface, forming a crater, and some radioactivity together with some of any remaining bio-organisms mix with the ejecta. This is also the time scale over which the underground shock, the air blast, and strong seismic shocks take effect. A zone of compacted and subsequently fractured rock extending typically one-and-a-half to three times beyond the maximum cavity radius is created. The size of the fissures in this fracture zone depends on the nature of the rock and the details of the geology (e.g., presence of perched water and other inhomogeneities).

Period 4. From seconds to hours after the explosion, during which the fallout cloud moves downwind from the explosion and the radioactivity in it may fall or be rained out.

Venting Time, Cavity Radius, and Temperature (Periods 1 and 2)

In what follows we present estimates of the cavity radius after the cavity stops growing in any direction but upwards (i.e., upon rarefaction), the temperature when the cavity vents to the atmosphere, and the amount of rock/soil vaporized and melted during the early part of Period 2. The masses melted and vaporized affect the cavity radius, the cavity temperature, and the radiation dose delivered to the bio-agents. The venting time determines the duration of the bio-agents' exposure to heat and radiation, whereas the rarefaction time is relevant to only the cavity radius. The cavity radius is important because no significant heat or radiation extends beyond it before venting occurs, meaning that any bio-agents not consumed by the cavity will not be sterilized before venting.

We note that "venting time" is an approximate concept. We estimate it by assuming that vertical cavity growth continues at a constant speed after the rarefaction wave returns to the cavity, and that venting occurs at the original ground surface. Both of these assumptions are probably wrong, though not enough to change the order of magnitude. In addition, venting does not occur all at once. These uncertainties affect the irradiation times of bio-agents.

We consider below cratering explosions with yields of 1 and 10 kilotons exploded at depths of 10 meters in granite and 10 and 30 meters in desert alluvium (one set of results is for basalt). Granite is a high sound-speed competent rock, while alluvium is more representative of soils with much slower sound speed. We also include some more qualitative remarks on concrete. No nuclear explosion occurred in concrete but aspects of the phenomenology of such an explosion may be inferred, and they could be important in evaluating the effects of a nuclear weapon on very hardened targets. The depths were chosen as optimistic representatives of what some penetrating projectiles may be capable of. Our estimates were made on the basis of scaled shock arrival and cavity growth normalized to these results, together with approximate equations of state data for the media in question, shown in Table 1.

Table 1. Some Medium Properties

Property	Granite	Alluvium
Bulk density [g/cc]	2.67	1.52
Dilatation sound speed [m/msec]	5.44	0.82
Internal energy to melt [10^{12} ergs/gram]	0.035	0.075
Internal energy to vaporize [10^{12} ergs/gram]	0.219	0.229

Sources: Adapted from James F. Shackleford, ed., *CRC Materials Science and Engineering Handbook*, 3rd ed. (Boca Raton, Fl: CRC Press, 2001); and from Teller et al., Table 4.2, p. 162.

We begin with some qualitative comments on penetration into rock. Data and calculations from Young et al.[10] lead to an upper limit estimate of 10 meters penetration for some types of rock, using reasonable parameters for the projectile weight, diameter, and configuration (see Appendix 1). Antoun, Lomov, and Glenn[11] show that five successive penetrators into the same hole in granite penetrate a total of only 5.6 meters, with the first bomb penetrating 2.1 meters and the fifth 0.4 meters. Nelson[12] estimates a penetration of 12 meters for a 4-meter long projectile into concrete. Glenn[13] notes that concrete structures are typically not well-confined, allowing lateral motion and thereby limiting penetration. Putting these data together and noting that the variation of penetrability with soil and configuration parameters is fairly slow, it seems unlikely that penetration into any competent rock would exceed 10 meters, although the details would depend on the parameters of the target site and on the design of the projectile. Penetration into granite would in all likelihood be significantly less.

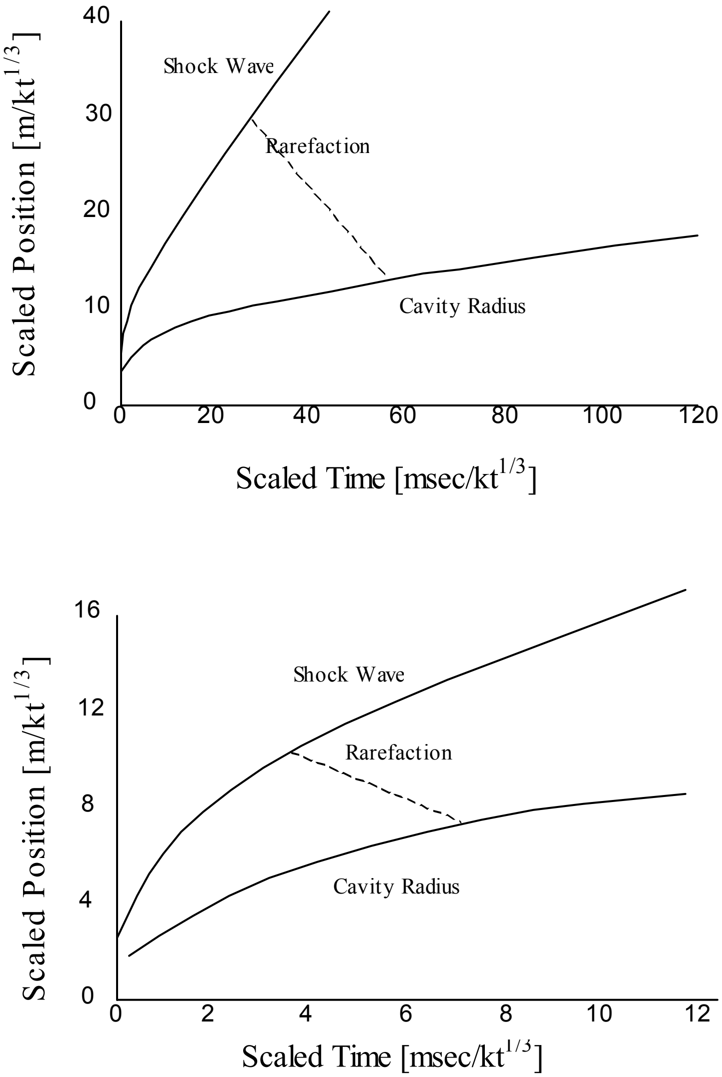
Since nuclear explosives were not detonated in large concrete structures, we do not have phenomenology data for such events. Explosions did occur in granite, basalt, tuff, and other rocks. We show in Table 2 and Figure 1 and in Table 3 and Figure 2 some estimates of cavity parameters for detonations in alluvium and granite, respectively. Estimates of venting times and cavity radii are based on interpolation and extrapolation to early times from Plowshare data and calculations (see Appendix 2). Estimates of the amount of ground material vaporized and melted can be made by scaling from data mainly from the Sedan (for alluvium) and Hardhat (for granite) events.

Table 2. Values at Venting Time, Alluvium

Yield, DOB	Venting time [msec]	Cavity radius [meters]	Tonnes vap.	Tonnes melted
1 kt, 30 m	>200	13	10^2	10^3
10 kt, 30 m	>100	18	10^3	10^3 - 10^4
1 kt, 10 m	30	6	10^2	10^3
10 kt, 10 m	9	8	10^3	10^3 - 10^4

Table 2 and Figure 1 apply to desert alluvium but may be reasonably representative of other soils such as soft clays. Most results were scaled from the results for the Sedan event, a 100-kiloton cratering shot in alluvium, with some additional information from the scaled shock history obtained from 19 detonations in alluvium, using chemical or nuclear explosives. These data did not permit scaling for the 10-kiloton explosion at 10 meters DOB. The values for that case were calculated using a single experimental early shock arrival time[14] (average of 14 alluvium shots) assuming that the ratio of specific heats γ for the vaporized medium was 1.1, the sound speed in the solid medium was 0.82 meters/millisecond, and the cavity did not slow down much over the first few milliseconds. All these assumptions are thought to be plausible but the result is nevertheless only a rough estimate.

Figure 1. Scaled Shock Position and Cavity Radius versus Scaled Time for Alluvium



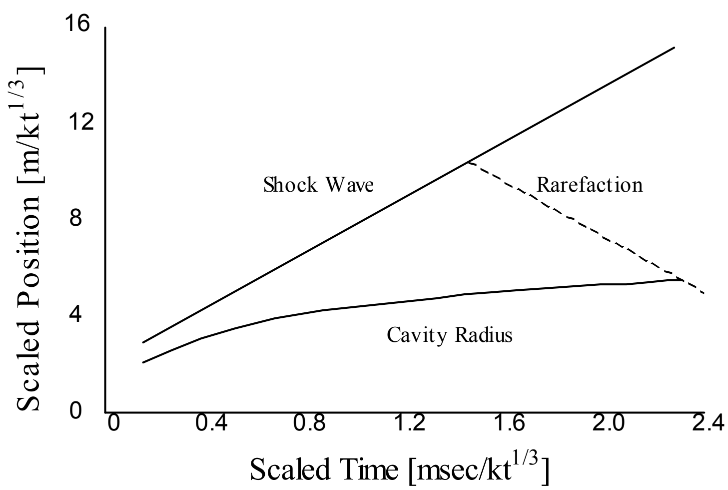
Source: Adapted from Teller et al., Figs. 4.12, 4.33, 4.34 and 4.40.

At the very early times (a few milliseconds) corresponding to maximum expected penetration into granite, calculations of the parameters relevant to bio-agent sterilization are particularly uncertain. At those depths of penetration, the explosion phenomenology is intermediate between that of surface explosions and buried explosions. Cavity radii are a few meters, and temperatures are in the thousands of kelvin briefly. Non-hydrodynamic energy transfers are still taking place. The following cavity parameters for explosions in granite should be accorded particular uncertainty.

Table 3. Values at Venting Time, Granite

Yield, DOB	Venting time [msec]	Cavity radius [meters]	Tonnes vap.	Tonnes melted
1 kt, 10 m	6	6	60	400
10 kt, 10 m	2	8	600	4000

Figure 2. Scaled Shock Position and Cavity Radius versus Scaled Time for Granite



Source: Adapted from Teller et al., Figs. 4.4, 4.7, 4.27, and 4.40.

In the explosions considered here, the amount of weapons material vaporized will be insignificant compared to the amount of rock/soil melted and vaporized. The Hardhat and Sedan data on vaporization and melting also allow us to estimate the shock pressures at the maximum radius where vaporization takes place. From those pressures and the corresponding Huguenot compressions, a rough guess can be made of the temperature and the associated degree of dissociation and ionization at the completion of vaporization. The gas cavity behind the expanding shock is then assumed to expand adiabatically since heat transfer mechanisms from the gas cavity are relatively slow. (Of course, the energy transfer across the shock ahead of the gas cavity is anything but adiabatic.) This method leads to venting temperature estimates in the range of

1000 kelvin for 30 meters DOB in alluvium and a few thousand kelvin for 10 meters DOB for either material. These estimates are only good to a factor of 2 either way. Details are given in Appendix 3.

The hole to the surface left by a penetrating projectile could affect the phenomenology. The early-time phenomenology of a penetrating projectile in particular will differ from that of a stemmed cratering explosion. The extent of this effect will depend on the diameter of the hole. Given that information, a rough estimate of the effect can be made by assuming that the cavity gas moves at the speed of a rarefaction wave through the hole to the surface. At the same time, the shock moves into the ground around the hole more rapidly than the bulk of the material moves up the hole, causing the hole to tend to close. The direction of these changes will be to lower pressure and temperature somewhat at vent time, although it is not clear by how much. The effect on cavity dimensions and exposure times (which scale as the third root of the pressure) is likely to be even smaller. A two-dimensional computer calculation would be needed to describe the phenomenology more accurately.

If the targeted bio-agents are in a structure containing tunnels, corridors, or any large empty spaces, the early time phenomenology is likely to be affected more seriously. If a significant fraction of the energy goes into these spaces, cavity formation will be altered and the times and temperatures noted will change. In the second section of this paper, we consider one particular such structure and estimate how the temperature and radiation profiles are affected.

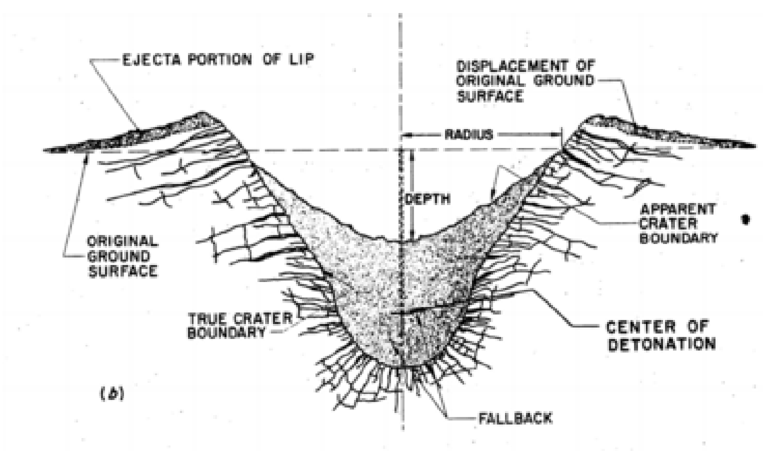
Depending on the construction of the target, concrete may provide some or much of the material vaporized and melted, and that in turn will affect the size of the cavity at venting, the time before venting, and the temperature at that time. Concrete has lower tensile and compressive strength than competent rocks, somewhat lower compression and sound wave velocities, and considerably more water (20-50 percent versus a few percent).[15] Those characteristics are consistent with estimates of deeper potential penetration by projectiles into concrete than into rock, perhaps to 20 meters; larger maximum cavity radius, exceeding 10 meters for the yields and DOB considered; and times of exposure on the order of tens of milliseconds. Concrete is not a single material so far as such important parameters as vapor pressure and speed of sound are concerned; thus, we limit ourselves to qualitative considerations. Any quantitative prediction of the phenomenology and effectiveness of a nuclear explosion in a concrete site will be affected by mineralogy, porosity (compactibility), cementation, weathering, and water content, as well as by the details of the concrete emplacement in the surrounding geological medium.

For the purpose of determining effects on buried bunkers containing bio-agents, we note that, without specifying the construction and materials of the bunkers and the nature of the bio-agents' containers, only order of magnitude estimates are valid. Even with those specifications, a complex calculation is needed to do much better than order of magnitude estimates presented here.

Crater Parameters (Period 3)

After the cavity gases vent to the surface, the temperature and pressure in what was the cavity drop rapidly, their energy transferred to the kinetic energy of the ground and debris. This material has been observed to rise higher than 600 meters above the surface. As it falls back in and around its original location, it compacts the ground further. In the end, the typical shallow crater results, with a lip around its edge, shown in Figure 3.

Figure 3. Crater Schematic



All of the cases presented will create large craters, described in Tables 4 and 5. The craters are surrounded by lips of varying heights equal to a significant fraction of the crater depth and almost as wide as the crater radius. The craters are partially filled with the materials originally ejected, in the form of rubble or compacted material depending on the geology. Geologic variables, such as water content, will change the results significantly. The hole left by a penetrating projectile may affect crater formation, though the extent is likely to be small.

Table 4. Craters in Dry Alluvium

Yield @ DOB	Crater radius	Crater depth
1 kt @ 30 m	45	38
10 kt @ 30 m	80	46
1 kt @ 10 m	38	20
10 kt @ 10 m	64	40

Table 5. Craters in Basalt

Yield @ DOB	Crater radius	Crater depth
1 kt @ 30 m	43	23
10 kt @ 30 m	80	42
1 kt @ 10 m	36	20
10 kt @ 10 m	No data	No data

Source: Boardman, Rabb, and McArthur in *Proceedings of the Third Plowshare Symposium, Engineering with Nuclear Explosives* (Berkeley: University of California Press, 1964), p. 122.

No data was available to us for cratering in granite, so the estimate presented in Table 5 was scaled from data pertaining to basalt, a rock with acoustic and other properties intermediate between granite and alluvium or soil. While two digits are presented, we judge only one to be significant. Again, the data available to us did not permit scaling to the case of 10 kilotons at 10 meters DOB without further calculations about the effect of possible non-hydrodynamic energy transfers.

Pressures versus Distance from the Explosion (Periods 3 and 4)

We show in Table 6 peak stresses at various distances from fully contained explosions in granite. These are peak stresses, not enduring pressures. Cratering explosions will not couple to the ground as well as fully contained explosions. A two-dimensional calculation extending several hundred meters is needed to provide more accurate answers. Granite and other rocks have non-zero yield strengths so that the scalar pressures must be replaced by the stress tensor in these calculations. For comparison, a 5-kiloton fully contained explosion in granite, Hardhat, gave a peak radial compression stress exceeding 1 kilobar at 100 meters and exceeding 100 bars at 500 meters.

Table 6. Radii for Some Peak Stresses, Granite

Yield	Radius at 1 kbar [m]	Radius at 3 kbar [m]	Radius at 20 kbar [m]
1 kt	60	40	15
10 kt	140	90	30

Source: Scaled from Teller et al., Fig. 4.4, p. 132, and Fig. 4.26, p. 165, using Table 1.

In alluvium and other soils, the pressure falls off more rapidly than in rock. Soils such as alluvia have little or no yield strength. Alluvia have a variety of properties and cannot be characterized to obtain reliable pressure-distance relation at large range without detailed geological knowledge. Even when alluvium is well characterized on the average, it exhibits significant local variations. Inhomogeneities are the rule. Keeping these uncertainties in mind and extrapolating the fit to data given in Teller et al.,[16] we get a peak pressure of 1 kilobar at 40 meters for a 1-kiloton blast in alluvium.

The hole left by a penetrating projectile is again likely to have little effect on these and other late-time results.

II. Destroying Bunkers and Deactivating Bio-agents

This section identifies the mechanisms that can destroy bio-agents and bunkers, and describes the extent to which an underground nuclear blast can destroy them. In estimating the effect of penetrating nuclear explosives against buried bunkers containing bio-agents, a distinction must be made between what destroys the bunker and what destroys the bio-agents. The bunker is destroyed by some combination of heat, pressure and other shock phenomena. On the other hand, heat and radiation are the mechanisms that deactivate the stored bio-agents. A conservative but realistic criterion for destroying the bio-agents themselves may thus be whether the explosion delivers enough heat and radiation to destroy the bio-agents before they can vent to the surface. After venting, other effects such as atmospheric exposure and fallout might deactivate the escaped bio-agents, but their effectiveness is more uncertain.

Deactivating Bio-agents by Radiation and Heat

We turn to the destruction mechanisms for the bio-agents and begin with radiation effects on bio-agents. Bio-agent sterilization criteria exist for exposures similar to the tens-to-hundreds of milliseconds before venting. The commercial standard for sterilization is an integrated radiation dose of just 2.5 megarads, and other authors suggest that a dose of 1 megarad should suffice.[17] The specific nature of the bio-agents and their storage media is likely to matter, so that our results should be considered only as indicative.

The effectiveness of the radiation from a nuclear explosion depends on the storage configuration of the bio-agents and the precise location of the explosion with respect to this configuration. In a brief study such as this one, there is no possibility of surveying all or even most of the likely configurations and locations. For the purpose of this section, we consider only two cases that encompass a range of the relevant parameters.

Case 1. The detonation takes place inside a large reinforced structure (bunker) that is empty except for some 1000 barrels containing 200 liters each of bio-agents in solution. This case was examined in detail by Hans Kruger,[18] who posited a bunker 60 meters in length, 10 meters high and 10 meters wide with walls made of 1-meter thick concrete, with the top of the bunker 10 meters below the surface.[19] We assume the weapon has penetrated exactly inside the bunker, and that no other agent material is stored in nearby rooms. These assumptions imply certain fortuitous circumstances: pinpoint target location and weapon delivery; shallow target depth; and simple bunker construction. As such, they represent one kind of limiting case.

Case 2. The detonation takes place in the ground, either because the bio-agent containers are buried separately in the ground, or because the detonation takes place outside the bunker.

For each case we review the sequence of events that may lead to exposure of the bio-agents. It is useful to break down this sequence of events into four processes, separated in space and/or time. Again we tie these processes to the four periods discussed in section I of this report.

1. Prompt Gamma Irradiation (Period 1)

About 5 MeV per fission or $1.2*10^{18}$ ergs/kt appear as prompt gamma rays.[20] The absorption coefficient for 0.5 to 2 MeV gammas in most media ranges from 0.05 to 0.1 cm^2/g, giving a mean free path of 5 to 10 centimeters for a density of 2 g/cc. This leads to extremely high doses (in excess of 10^{10} rads) for small masses (a few tonnes or less) in the immediate vicinity of the explosive. What the irradiated mass actually is will depend on the initial volume from which the gamma rays are generated and on the nature of the immediately surrounding material. For Case 1, the material would be any barrels containing bio-agents that have clear lines-of-sight to the explosion. If the bio-agents are in a liquid solution, as Kruger assumes (endnote 17), the density is probably close to 1 g/cc. If they are in solid form, as anthrax spores for instance, the density may be of the same order of magnitude or lower. For Case 2, the material is the surrounding soil or rock medium. Either way, the amount of bio-agents effectively irradiated by this process will in all likelihood be a small fraction of the total.

2. Prompt Neutron and Capture Gamma Irradiation (Period 1)

About 5 MeV per fission or $1.2*10^{18}$ ergs/kt appear in the form of 2 MeV neutrons, of which some fraction is reabsorbed to create further fissions.[21] That fraction will depend on the details of the explosive, but it has been estimated that there is about one excess neutron per fission or about $0.6*10^{18}$ ergs/kiloton (based on $1.46*10^{23}$ fissions/kt). In addition, an additional 10 MeV of gamma rays ($2.4*10^{18}$ ergs/kt) appear immediately at the site of the neutron capture[22] and are again absorbed within 5-10 centimeters.

The absorption cross section for 2 MeV neutrons in most materials is small compared to the scattering cross section and rises rapidly as the neutrons lose energy, so that the distance over which the neutrons are absorbed (the effective absorption mean free path) is essentially the slowing down distance. That distance depends on the specific elements in the surrounding medium, especially the light atom content, so that water content, for instance, will make a difference. Basalt is a dry rock that is about 50 percent SiO_2, less than 2 percent water, and the rest other oxides.[23] The total neutron cross section in the 1-2 MeV region on Si is 1-3 barns.[24] The n-γ cross section in the 1-2 MeV region on Si is 5-60 mbarns going to 500 mbarns in the 400 keV region,[25] giving a mean free path of a few centimeters. Again this gives a very small irradiated mass in both our cases, even taking into account the fact that several collisions must occur before capture and that the capture gamma mean free path must be added to the total. The neutrons also give rise to a significant induced radioactivity. We take up this effect along with the effect of radioactivity due to fission products in the next subsection.

3. Irradiation by Radioactive Decay before Venting (Period 2)

Over the next few milliseconds, the radioactive fission products and induced radioactivity mix with the vaporized material. In order to irradiate this material, mixing only has to take place down to dimensions comparable to the mean free paths involved. Given the high temperature and sound speed, such mixing will occur in a short time compared with the few milliseconds available. Given the masses of material vaporized shown in Tables 2 and 3, initially all of the radiation is contained within this material. Some mixing and irradiation may also occur with the molten material and the walls of the cavity.

We estimate Case 2 first. There, the presence of barrels of bio-agents should not affect the previously described phenomenology much. Tables 2 and 3 show that there is an interval before venting on the order of 10 milliseconds if the explosion takes place at 10 meters DOB, and on the order of 30-100 milliseconds if the DOB is 30 meters. During this time, the energy of fission products' gamma radioactivity (from Pu-239 fission, but other fissile material will not give very different values) is on the order of 0.55 MeV/fission-second.[26] Using a mean gamma energy of 0.5 MeV and a mean beta energy of 1.2 MeV[27] and a ratio of 3:2 gammas to betas/fission/second,[28] we infer a beta activity at 1-10 millliseconds of 0.55*(1.2/0.5)*(2/3)=0.88 MeV/fission-second for a total of 1.43 Mev/fission-second or about $2*10^{23}$ MeV/kt-second.

With uniform mixing of the radioactive debris with the vaporized material (whether soil/rock or bio-agent solution), at least on the scale of centimeters, and for the yields and masses cited in Tables 2 and 3, we obtain less than the 1-2.5 megarads dose required to sterilize most bio-agents if the time available is on the order of 10 milliseconds, i.e., for 10 meters DOB. The radioactive dose delivered is somewhat above the required 1-2.5 megarads if the irradiation time goes up to and beyond 100 milliseconds, i.e., for deeper blasts. The actual time of irradiation prior to venting will be uncertain for the reasons adduced in the phenomenology section. In addition, irradiation will probably not be uniform. The amount of bio-agent irradiated above the criterion quoted may be small compared to the total amount stored, depending on the fraction of the bio-agents in the cavity (that is, depending on whether the cavity consumes the entire storage site). We believe our rough estimates are sufficient to state that, for 10 meters DOB, there is little or no assurance of complete sterilization of the material within the cavity. For 30 meters DOB, there is more assurance of complete sterilization of the material within the cavity. Our rough estimation methods cannot give more quantitative results, but we note that uncertainty about the position of the explosion with respect to the exact layout of the bio-agents will also translate into less assurance of the extent of sterilization.

If the explosion takes place within a fortified bunker such as described by Kruger (Case 1), the sequence of events after the explosion can be expected to be significantly modified. In particular, mixing and time available before cratering are likely to be modified. Neither we, nor Kruger (in the document referenced) have carried out the two- or three-dimensional calculations needed to describe the coupled processes of irradiation, mixing and hydrodynamic motion that actually take place. We attempt to estimate the effect of finite irradiation times and motion in what follows, but clearly this can only be done very approximately.

The static calculation done by Kruger using Monte Carlo N-particle transport cannot be improved upon here. Kruger obtains different results according to how much of the postulated 200 tonnes of bio-agent has been vaporized and according to whether the dose is measured in the liquid or the vapor, but all his results lie in the 2-10 megarads per kiloton per second, with little change during the first 100 milliseconds.[29] Over the first ten milliseconds, therefore, this number again falls short of the 1-2.5 megarads criterion for sterilization. Over 100 milliseconds, there may be complete sterilization, depending on the dose rate, which in turn depends on how much material is exposed. This is in accordance with Kruger's conclusion that sterilization of bio-agents would take from half a second to a second unless very little of the solution was vaporized.

It follows from the above estimates that, for both Case 1 and Case 2, the completeness of sterilization may well depend on irradiation after venting begins and during cratering, when conditions are much harder to predict. This is taken up below. In addition, at any DOB, the extent of sterilization depends on the details of the target configuration.

4. Irradiation in the Crater and Lip (Period 3)

The process of cratering, briefly described in the first section of this report, takes many milliseconds, during which the stored bio-agents, whether vaporized or not, and the surrounding medium undergo complex motion. As the cavity vents to the surface and cratering takes place, whatever bio-agents remain in the highly radioactive crater and lip are exposed to further radiation. In addition, ejected bio-agents will be exposed to atmospheric radiation and possibly undergo desiccation. Further research is needed to gauge these effects.

A majority (but not all) of the bio-agents that do not remain underground will be trapped in the highly radioactive crater and lip material. Scaling the volume of broken rock in the Danny Boy explosion (Teller et al., Table 4.6, pp. 190-191), we obtain masses of broken rock on the order of 10^5 tonnes, in which the bio-agents will be mixed, no doubt inhomogenously. This material is about 1000 times the mass mixed into the cavity gases. The irradiation time, on the other hand, will go from milliseconds to however long the material is left undisturbed. Because the cratering process of Period 3 takes place at lower temperatures where the materials remain solid, there will not be the degree of fine mixing that took place in the cavity. Rather, there will be cold and hot spots where the bio-agents receive lower or higher irradiation. We are unable to estimate this effect.

From the above analysis, we conclude that simple estimation methods in the absence of detailed target knowledge do not provide a sure way to determine how much of the bio-agents in the bunker will be destroyed by radiation. There is a small volume near the explosion, a few gamma ray mean free paths or neutron slowing down lengths, that will receive enormous doses of radiation, but that volume, a few cubic meters, is unlikely to contain most of the bio-agents. The much larger (hundreds to thousands of cubic meters) volume of the cavity before venting will contain initially all of the highly radioactive fission products and induced activities, but only for at most a few tens of milliseconds. In that time, the fission product radioactivity and the induced radioactivity generated will give a dose that depends on the details of the configuration and of the material surrounding the bio-agents, but that may be comparable to though not clearly larger than the sterilizing dose. Finally, much or all of the bio-agent mass will be mixed with the highly radioactive fission products and induced activities over a much longer time during the cratering process, in the crater and lip rubble. Over times exceeding several seconds, there is little question that the bio-agents that remain within gamma or beta range of the radioactive material will receive one megarad or more. There is no way to know, however, how the bio-agents are distributed in the debris and eventual fallout without much more detailed calculation and experimentation. In particular, it is likely that the bio-agent solution, because of differences in chemistry and volatility, will fractionate differently than the radioactive material, with a consequent different distribution among fallback material and fallout.

5. Heat

Heat may be a better destruction mechanism than radiation, although here too there are uncertainties. Cavity temperatures are on the order of 1000 kelvin for a few milliseconds up to sometimes hundreds of milliseconds (see Appendix 3). Data regarding the effectiveness of this exposure to heat of various specific bio-agents for such periods indicate that temperatures on the order of or exceeding 1000 kelvin for times on the order of or exceeding 10 milliseconds would deactivate most chemical and biological agents.[30] Based on our estimated temperature and times, bio-agents exposed to cavity temperatures will therefore be sterilized. What happens outside that time and space window, i.e., subsequent to cavity venting and in the fracture zone that extends beyond the cavity, is much more uncertain.

In a bunker (Case 1 above), the initial radiation from the explosion will raise the temperature of the barrels of bio-agents within a few meters to the same or higher temperature as we calculated for the ground material for the same distance. The same is true for Case 2. Beyond distances roughly equivalent to the cavity radii calculated in Tables 2 and 3, however, heat will have to be transferred to the still solid or liquid bio-agent in the time available before cooling due to venting takes place. Radiative transfer is unimportant at the temperatures then prevailing. Convection will determine the fineness of mixing of the non-vaporized bio-agents with the hot gases during that time (Period 2), which will matter, since heat from the gas will have to diffuse into the still solid or liquid material. There are only some tens of or at most a few hundred milliseconds to communicate the heat. A very rough estimate of the heat diffusion in a gas at 10^4 kelvin leads to diffusion times on the order of a second for distances on the order of millimeters at most.[31] Thus 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 if the mixing takes place only on a centimeter scale or larger. Again a much more detailed analysis, coupled with experiments, is needed to make a more accurate estimate of the effectiveness of the explosion at heating the mixture.

We note that much more accurate calculations are within the reach of today's computers and that useful experiments could be carried out with suitably instrumented high-explosives and tracer chemicals, without having recourse to nuclear explosions or actual use of bio-agents. On the other hand, uncertainties regarding the disposition of bio-agents in target locations and the position of the explosion with respect to the target will remain.

Deactivating Bio-agents by Atmospheric Exposure

If any active bio-agents were released into the atmosphere, they could be deactivated by various natural mechanisms, including oxygen toxicity, pollutants (ozone, smog), relative humidity, temperature, and UV and visible light. These environmental factors deactivate biological agents by desiccation (drying them out), by rupturing the cell wall, or by interfering with cellular processes. There is not yet any definitive model of the deactivation of bio-agents in the atmosphere. As noted earlier, the bio-agents have a different chemistry and will fractionate and condense differently from the radioactivity. Their lifetimes are also subject to different laws. A coupled calculation of these factors would need to take into account not only the chemistry and lifetime of the bio-agents, but also any effect from the long-time exposure to the fallout radiation. We have no data regarding the fate of the bio-agents mixed in with the radioactive cloud.

Preliminary calculations by Hans Kruger[32] indicate that, under the same weather and explosion conditions, the distance at which a given level of casualties from anthrax spores occurs considerably exceeds the distance at which a similar level of casualties from radioactive fallout occurs, unless essentially all of the spores are destroyed. If the disease carried by the bio-agents is more communicable than anthrax, the response may not be linear with exposure, as it is with radiation. More extensive computer models should cast some light on these phenomena.

Destroying the Bunker

During Periods 2 and 3 after the explosion, as noted in the phenomenology section, a shock wave propagates outward, fracturing the zone of rock beyond the cavity. This fracture zone typically extends one-and-a-half to three times beyond the cavity radius. Most structures within that zone will be destroyed, but bio-agents in that zone will probably not be sterilized immediately because, except for some fraction that may be affected by leakage through the fractures, they lie beyond the range of the destructive heat and radiation. Bio-agents that are not sterilized by the radiation and heat might escape aboveground through these fractures or during the cratering process, perhaps long after the explosion.

A nuclear explosion will affect a buried bunker, such as the one postulated by Kruger, differently from ground material. The pressure interactions at the boundaries will be complicated and the effect on the bunker will depend on its construction and materials. Despite these differences, which can only be explored with the more complex calculations and experiments noted earlier, an upper limit estimate of the destructive potential in the fracture zone can be obtained by examining the pressures to be expected beyond the cavity given in Table 6 and the following material in section I. In granite the peak compressive stress for a fully contained explosion exceeds 1 kilobar to 60 meters for a 1-kiloton explosion and to 140 meters for 10 kilotons. Even in a dissipating medium like alluvium, the peak compressive stress exceeds 1 kilobar out to 40 meters.

The survival of underground bunkers at such pressures will depend on their construction. There is evidence from Hardhat (5 kilotons in the Climax granite at NTS) and Pile Driver (61 kilotons in the same formation) that underground structures survived 1 kilobar and some suitably reinforced structures survived 2 kilobars roughly unscathed.[33] Thus, properly designed bunkers in granite may survive 2 kilobars. On the other hand, completely unlined and unreinforced tunnels in granite can probably be collapsed at stress levels only 1/10 as high. Strongly reinforced underground structures, such as the hardest missile silos, were believed to be hardened to pressures of at most 6,000-8,000 psi or 500 bars, but their main vulnerabilities were associated with fragile equipment that had to be shock-mounted. Thus, if a penetrating 1-kiloton nuclear weapon were detonated inside a bunker, the hardest of bunkers will be destroyed unless there are parts that extend much farther out than 40 or 60 meters from the explosion.

One may speculate that a storage bunker will not be as hard as the structures noted above, since such engineering is very expensive to design, test, and build, and requires specialized technology. In that case, the bunker could be destroyed one hundred meters from the explosion or farther. It should be noted that the pressures indicated are upper limits that will become less and less valid as the scaled DOB decreases and the explosion behaves less and less like a fully contained explosion.[34] In particular, they are not reliable for the 10-meter DOB cases. Bunker contents, such as containers for instance, could be much harder or much softer than the numbers above. In general, it is easier to harden small volumes with relatively simple technologies than large spaces such as tunnels.

III. Surface Effects of Penetrating Explosions

Radioactivity

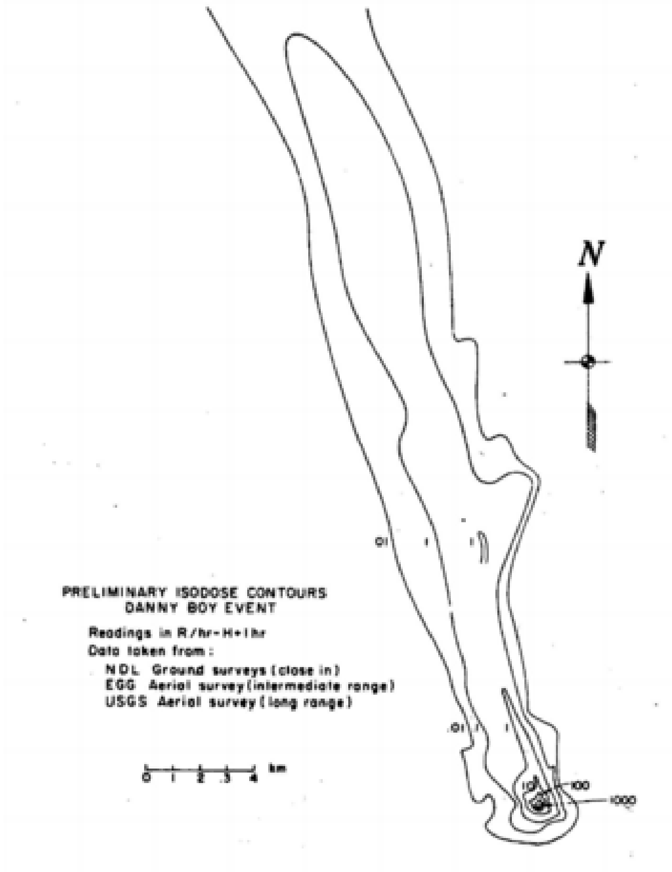
Because penetrating projectiles do not bury themselves deeply enough to contain even low-yield explosions, there will be significant aboveground effects. When the explosion vents to the surface, the resulting large upward pressure gradient propels material into the atmosphere. The hot, radioactive material in the cavity, together with the other material surrounding it, disperses aboveground. Any mixed-in bio-agents, sterilized or not, will also disperse.

The majority of the radioactivity and remaining bio-agents, along with whatever was in the cavity at the time of venting, is trapped in the debris that falls back into the crater or on the lip, making the crater and vicinity intensely radioactive. The remainder is suspended in the air during the fallback period and goes into the fallout plume, which is carried away from the site of the explosion by wind and which falls back to earth at various distances depending on the wind, the medium in which the explosion occurred, and rain. How much of the radioactivity and bio-agents in this fallout plume (whether sterilized or not) are carried away depends sensitively on the scaled DOB, the type of material volatilized, the size of the particles on which the radioactivity and bio-agents condense to the extent they do condense, and the chemistry of the radionuclides and bio-agents as they react with atmospheric and soil components, especially any vaporized water.

For the deeper DOB considered here, e.g., 1 kiloton at 30 meters, and for the media considered, probably less than 10 percent of the radioactivity will go into fallout. For the shallower DOB, e.g., 10 kilotons at 10 meters, the fraction will be larger. Absent detailed knowledge of the emplacement site, it is not possible to give accurate numbers. For orientation, we reproduce below the fallout patterns for Danny Boy (0.42 kilotons at 43 meters in basalt) and Sedan (100 kilotons at 96 meters in desert alluvium).

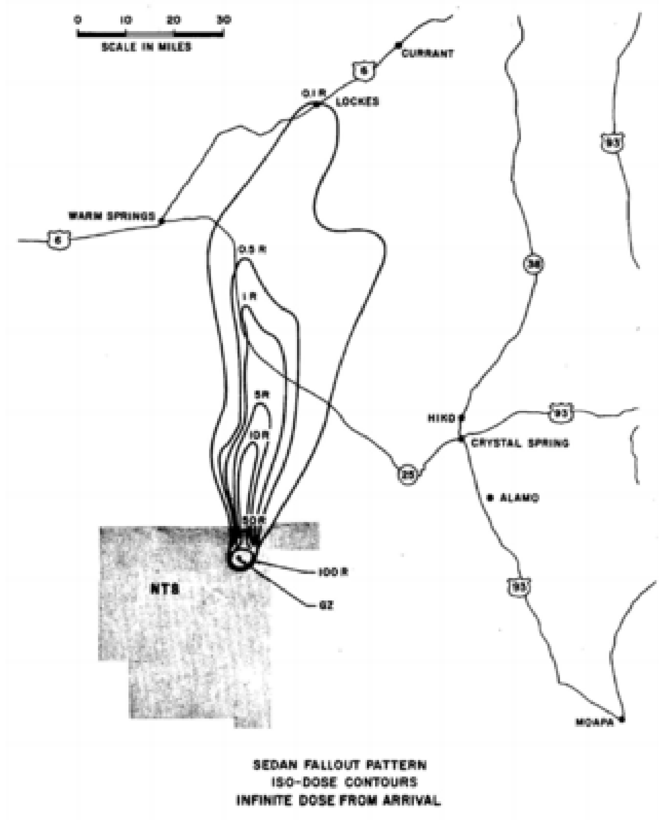
Past experience indicates that 70-90 percent of the fallout will be deposited within 10 miles.[35] For explosions at the shallower DOB in volatile-containing media, such as most concretes, the fallout could extend farther.

Figure 4. Fallout Pattern at H+1 Hour, Danny Boy



Source: From Teller et al., Fig. 3.13, p. 109.

Figure 5. Integrated Fallout Pattern, Sedan



Source: From Teller et al., Fig. 3.14, p. 110.

Some of the fallout-induced dose rate near ground zero could be quite high. Assuming for the sake of illustration that 0.1 kiloton of fission fallout falls within an hour over 25 square kilometers, something that could result from the any of the 1-kiloton explosions described above, the dose rate three feet above a flat ground would average about 30 rads/hour. If the fallout were more concentrated, because of rainout or a greater fraction of the radioactivity going into fallout, the dose rate could well be 10 times as high or even more.

Fallout calculations that have been carried out recently for yields ranging from 0.1 to 1000 kilotons in the case of flat terrain and a typical moderate wind confirm this rough estimate.[36] Burial was shallow, 5 meters in dry rock and 20 meters in soil. For yields in the 1- to 10-kiloton range, the areas over which the initial 24-hour dose exceeds the LD50 dose[37] of 450 rads are in the neighborhood of 10 square kilometers. For yields in the sub-1-kiloton range, this area is on the order of one square kilometer.[38] The radioactivity after one minute decays very approximately as $(\text{time})^{-1.2}$.

As the explosion occurs nearer to the surface, the above-surface effects come to resemble the effects of a surface burst. The fallout effects are that more radioactivities and other materials vent, the material disperses more finely, and the chemical interactions of the material with the air and other dispersed matter will play a greater role. Other factors being equal, local fallout decreases and distant fallout increases. Much the same can probably be said of any remaining bio-agents.

The effect of the hole left by a penetrating projectile, or of any other source of early leakage, on the vented radioactivity could be significant if the hole does not close soon. Since most of the radioactivity goes into the debris anyway, there will be little effect on the amount vented; however, there could be significant effects on the proportion of the radioactivity that falls back into the crater versus far away, the composition of the fallout, the particle size on which volatile radioactivity condenses, etc.

Low levels of radioactivity will be detectable at great distances.

Air blast

Damage due to air blast—that is, the coupling of the detonation energy to the air after cratering—depends not only on scaled DOB, but also on refraction and reflection in the atmosphere and at the air-surface boundary. A standard curve for a 1-kiloton surface explosion shows that the air blast pressure will exceed 10 psi (causing severe structural damage to or collapse of buildings) inside of 300 meters, exceed 1 psi (significant damage to structures) out to 1 mile, and exceed 0.03 psi (some window breakage and plaster cracks) out to 10 miles. These estimates are for still air at 300 kelvin, with no reflection or refraction effects. Those effects could (and have in the past) led to higher values at greater distances.

The air-blast pattern for a cratering explosion differs from that for a surface explosion in several ways.[39] The upward direction of the initial shock lessens the blast in the immediate vicinity (perhaps by a factor greater than two for ranges less than a kilometer) of the explosion, but increases it farther out owing to refraction downward of the original shock. The higher yield, shallow-penetrating explosion will have an air blast pattern closer to that of a surface burst, while the lower yield, deeper-penetrating explosion will show this effect.

Damage to people is less well documented than damage to structures. The main cause of damage to people associated with the air blast will be flying objects, either picked up by the blast or torn from disintegrating structures. Damage to people can be expected from these causes out to a mile or so, again depending on the yield, DOB, and nature of surrounding terrain and structures.

The effect of the hole left by a penetrating projectile on the distant air blast should be minimal.

Seismic disturbances

Damage from seismic motion again depends on the yield and medium, and the DOB to some extent. Based on U.S.G.S.-developed equations for seismic velocity, a 10 cm/second velocity, generally accepted as the threshold for plaster cracking, will be experienced about 5 miles away from a 10 kiloton explosion in granite.[40] Some seismic damage may therefore be expected within that range. Granite can be expected to couple better to seismic waves than alluvium. The effect of the hole left by a penetrating projectile on the seismic disturbances should be minimal. The explosions described will give rise to seismic signals detectable around the world.

Conclusion

The results of this analysis suggest the following conclusions:

1. A penetrating nuclear weapon in the 1- to 10-kiloton range will deliver enough heat and radiation to sterilize all or nearly all bio-agents stored within 10-30 meters, depending on yield and DOB. This short range means that the explosion should occur within the targeted volume, which is an extremely exacting target location and weapon delivery requirement.
2. Whether all of the bio-agents in a given storage configuration are sterilized depends pivotally on the details of the storage configuration, particularly on the size of the bunker, the arrangement and shielding of the bio-agents in the bunker, or, if the agents are buried directly in the ground, on their spacing.
3. Structures and agent containers can be destroyed at distances that exceed the radius of bio-agent sterilization, so that any remaining active agents could be dispersed aboveground. Deeply buried targets will likely escape effective bio-agent sterilization.
4. At the depths considered, the nuclear explosions considered have major surface effects, such as the formation of an intensely radioactive crater area, lethal local radioactive fallout and possibly important radiological effects farther away, destructive air blast to distances of one to a few miles, and seismic effects. Radiation and seismic signals will be detectable at great distances.
5. The spread of any remaining live bio-agents will be subject to different fractionation and resuspension patterns than radioactive fallout, and may be affected by atmospheric exposure and fallout radiation. It seems likely, on the basis of preliminary calculations, that the dispersal of the targeted bio-agents or any significant fraction of them would cause casualties exceeding the casualties from surface effects of the penetrating nuclear explosions considered, assuming that the targets are well away from populated areas.

Our analysis has important limitations, in addition to the limitations imposed by targeting uncertainties. Among them are:

1. The effects of a bunker on the formation of the initial underground cavity and the subsequent phenomenology.
2. The geological characteristics of the area targeted.
3. The mixing, chemistry, lifetime, and resuspension of the specific bio-agents targeted during venting and cratering and later in connection with fallout.

4. The effect of the hole left by the penetrating projectile. We suspect that this last factor will not affect our main conclusions.

Better calculations and experiments could lessen or remove these limitations; however, the effectiveness and side effects of the explosion will continue to depend on very accurate targeting as well as detailed knowledge of the targeted emplacement, the geology, the nature of the bio-agents and their storage media, and the local atmospheric conditions.

Appendix 1. Maximum Penetration Estimate

We show here how calculations based on Young[41] lead to an upper limit estimate of 10 meters penetration for some types of rock, using reasonable parameters for the projectile weight, diameter and configuration. To show this, we reproduce below a nomogram excerpted from Young's article. While the article is over 30 years old, more recent work does not change the results significantly, given the other uncertainties in the situation. The nomogram, which summarizes a number of calculations, allows one to postulate a vehicle weight, an impact velocity, a soil constant characteristic principally of the tensile strength of the medium penetrated, and a nose performance coefficient characteristic of the penetration capability of the particular vehicle geometry, and from those assumptions to derive a penetration depth.

In what follows, we give a characteristic example. Readers can make different assumptions and obtain somewhat different results. Within realistic boundaries, however, the results do not vary so much as to lead to depths significantly different from the ones we discuss here, and therefore to conclusions that would be significantly different.

The weight of a payload carrying a nuclear explosive we take to be 2,000 lbs (the nomogram uses lbs and feet rather than SI units). This is a nominal value that could obviously be increased at the expense of range and cost. We use 2000 feet per second (FPS) for the impact velocity for the practical reason that the nomogram does not show higher velocities. Theoretically, impact velocities for 4000 FPS may be possible for steel projectiles before the projectile buckles, but it seems unlikely that a penetrator containing the components needed for a nuclear detonation could impact at anywhere near that velocity. We note that Glenn and his colleagues (endnote 11) use an impact velocity of about 1000 FPS with a very robust, well-designed penetrator. We use a soil constant of 1, which is slightly larger than what Young recommends for concrete[42] and almost surely too large for granite and similar rocks (high S numbers correspond to more penetrable materials). Finally we use a nose performance coefficient of 1, corresponding to what Young describes as reasonable in at least one case of relevance here.[43]

Those assumptions, which are optimistic with regard to penetration of a nuclear-armed penetrator so far as we know, lead to a penetration depth of about 33 feet or 10 meters for concrete or other fairly hard material.

Appendix 2. Estimate of Cavity Radius at Venting Time

In calculating these values (shown in Tables 2 and 3), we first used Figures 1 and 2, which were adapted from data and figures in Teller et al. Figures 1 and 2 show the cavity development and shock position as a function of time, beginning just after the immediate vaporization. (One can also calculate the vaporization radius from the internal energy needed to vaporize the ground material, as given in Table 1.) The shock position and cavity radius were scaled to a 1-kiloton blast from similar low-yield blasts in the respective ground material, and the rarefaction velocity was determined by the shock velocity, up to a maximum velocity equal to the seismic sound speed for the given medium.

For a given medium and depth of blast, to calculate the cavity radius upon rarefaction: 1) determine from the graph when and where the shock wave hits the ground surface; 2) from that point, project a rarefaction wave traveling back toward the cavity at the seismic sound velocity, or at the shock wave velocity if the shock wave has slowed to less than the sound velocity; 3) find when and where the rarefaction line intersects the cavity radius curve. This point is when the rarefaction wave reaches the top of the cavity and the lower half of the cavity ceases to grow, which gives the cavity radius and the time at rarefaction.

To calculate the venting time: 1) first add the time that elapsed during the propagation of the shock wave and the rarefaction wave; 2) determine the speed at which the cavity was expanding when the rarefaction wave reached the top of the cavity; 3) use that speed to determine the time it takes for the cavity to travel the remainder of the way to the original ground surface.

In summary, rarefaction time + (DOB – cavity radius) / cavity velocity = venting time.

Appendix 3. Estimate of Cavity Temperature before Venting

We calculate the cavity temperature at venting from a fit to experimental data on the cavity pressure in the medium of interest as a function of scaled radius. These fits are given graphically for granite in Teller et al. Figs. 4.25 and 4.26, and for alluvium in Fig. 4.32, supplemented in the case of alluvium by the estimates of vaporization mass and radius for Sedan.[44] We use the shock pressures so obtained and the Hugoniot relations for the appropriate medium from Table 4.3 to obtain a temperature as a function of effective molecular weight M using the ideal gas formula:

Pvent = rho * Tvent / mu, or,
Tvent / M = (12 * Pvent) / density.

In that formula, T is in kelvin, P is in kilobars and the density is in metric tons per cubic meter, which is the same as g/cc. There are several problems with that formula, which we discuss below, but we believe that the uncertainties do not take the temperatures outside the ranges quoted.

1. The shock pressure and Huguenot compression are valid just behind the shock. Going inward from the shock, both pressure and density drop. The results of more accurate difference solutions of the hydrodynamic equations show that the temperature as a result is approximately uniform, as shown schematically in Teller et al., Fig. 1.4c, p. 7. Physically, this may be thought to make sense because the initial central temperatures are high enough to make uniformity likely and the subsequent expansion of the cavity gases is not sufficiently rapid to create much temperature non-uniformity.

2. The degrees of dissociation and ionization of the cavity gases, which determine the effective molecular weight M, will change as the temperature drops. M has a minimum value of 2, corresponding to full dissociation and ionization, which is only reached at temperatures exceeding 10^4 kelvin. If the temperature is low enough so that only dissociation occurs, and if silicon dioxide is representative of the gas composition, M has a maximum value of about 20. In our calculations, we look for plausible combinations of Tvent and M at the end of shock vaporization. Looking at the range of plausible combinations leads to a probable factor of 2 in uncertainty regarding M values and Tvent.

3. The ideal gas formula given above relating the pressure and temperature in the gas immediately behind the shock is only approximately valid. For late-time expansion, we use the ideal gas law for adiabatic expansion, $TV^{(\gamma-1)}$=constant. Teller et al. assume $\gamma = 4/3$ (Teller et al., p. 136). Nordyke[45] uses even lower values of γ for the shock going into the ground, because of volatile releases and condensation that should not affect the behavior behind the shock at the temperatures of interest. For very short venting times corresponding to shallow DOB in granite, the gas may behave more like an ideal gas with $\gamma = 5/3$. The difference between $\gamma = 5/3$ and $\gamma = 4/3$ leads to another factor of 2 uncertainty in relating pressure to temperature.

Those uncertainties lead us to believe the temperature estimates are likely to be correct within a factor of 2 either way.

Here is a numerical example for 1 kiloton and 10 kilotons at 10 meters DOB in granite:

1. Get the shock pressure P at Rvap from Fig. 4.25, which is about 1100 kilobars for any yield.

2. Get the density just behind the shock at that pressure from Table 4.3, which gives 5.3 tons/cubic meter. (using the 2.67 g/cc original density).

3. Use Tvap/Meff=12*P/density to obtain Tvap/Meff= 2500. This Meff is the effective molecular weight at the vaporization radius, not later. Meff=4 gives Tvap=10^4 kelvin. A higher Meff leads to higher Tvap, and a lower Meff to a lower Tvap, where Meff should approach 2. At these early times, high temperatures are likely, and Meff=4 or so is good to a factor of 2.

4. Assume adiabatic expansion from the vaporization radius to the vent radius. Using γ=4/3,

$$TV^{(\gamma-1)} = TR^{3(\gamma-1)} = TR = \text{constant}.$$

Scaling Rvap from Fig. 4.25 gives Rvap=1.75 meters (which is consistent with Fig. 4.26). Using Rvent=6 gives Tvent=3000 kelvin.

5. For 10 kilotons in granite, we have the same Tvap=10^4 kelvin, but we must scale from Rvap=3.8 meters to Rvent=8 meters, giving Tvent=5000 kelvin approximately.

These temperatures are higher than those created by similar explosions in alluvium.

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[1] Hans Kruger, "Radiation Neutralization of Stored Biological Warfare Agents with Low-Yield Nuclear Warheads," UCRL-ID-140193, Lawrence Livermore National Laboratory (August 21, 2000).
[2] Lawrence Radiation Laboratory et al., *Proceedings of the Third Plowshare Symposium, Engineering with Nuclear Explosives* (Berkeley: University of California Press, 1964).
[3] See also Samuel Glasstone and Phillip J. Dolan, *The Effects of Nuclear Weapons*, 3rd ed. (U.S. Departments of Defense and Energy, Third Edition, 1977), pp. 58-63.
[4] Teller et al., *The Constructive Uses of Nuclear Explosives* (McGraw-Hill Book Company, 1968).
[5] Ibid, p. 129.
[6] Ibid, p. 132.
[7] A rarefaction wave is a region of lower pressure and density moving into a region of higher pressure and density, relieving that higher pressure as it goes.
[8] Milo D. Nordyke, "On Cratering: A Brief History, Analysis, and Theory of Cratering," UCRL-6578, Lawrence Livermore National Laboratory (1961).
[9] An absorption mean free path is the mean distance within which the neutron or gamma ray is absorbed. The absorption mean free path depends on the energy of the neutron or gamma ray. Absorption of neutrons may occur after a series of collisions (scattering) during which the neutron loses energy.
[10] C. W. Young, "Penetration Equations," Sandia National Laboratories (October 1997) and C. W. Young, "Depth Prediction for Earth–Penetrating Projectiles," *Journal of the Soil Mechanics and Foundations Division*, SM 3:813 (May 1969).
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[13] Lew Glenn, private communication.
[14] Teller et al., Fig. 4.40, p. 177.
[15] The conclusions presented are based on material constants in Charles T. Lynch, ed., *CRC Handbook of Materials Science* (Cleveland: CRC Press, 1974); on articles discussing rock characteristics and the relation of cavity radius to material strength by Nordyke, Hiuggins, Terhune, Cherry and Peterson, and Cameron and Scorgie in *Peaceful Nuclear Explosions* (Vienna: International Atomic Energy Agency, 1970); and discussions with Prof. Robert Tatum of Stanford University, to whom we are grateful.
[16] Teller et al., Fig. 4.32, p. 171.
[17] Hans Kruger, "Delayed Fission Debris Radiation Effect on Chemical and Biological Agents Stored in a Bunker," UCRL-130475, Lawrence Livermore National Laboratory (1998).
[18] Ibid.
[19] The Departments of Defense and Energy's "Report to Congress on the Defeat of Hard and Deeply Buried Targets" of July 2001 states that many buried targets are of the cut-and-cover design. Such targets are shallow-buried, often with only a single room. On the other hand, deeper, multi-room bunkers also exist. Our results do not depend on the amount of material stored in the bunker.

[20] See Table 6 in Department of Energy, Nuclear Physics and Reactor Theory Handbook (1993), <http://www.tpub.com/doenuclearphys/nuclearphysics31.htm>.
[21] Ibid.
[22] Ibid.
[23] Teller et al., Table 3.3, p. 96. These are bulk properties. Voids in the basalt may be filled with additional water. We thank Greg Mello for this and many other helpful comments.
[24] See J.K. Dickens, et al., "28Si (n, n'gamma) photon production cross sections for E(gamma) = 1.78 MeV, 5.0 <= E(n) <= 9.5 MeV," Oak Ridge Linear Accelerator (1975), http://www.nea.fr/dbforms/x4swdisp.cgi?10397.003; and, B.J. Atkins, et al., "Neutron capture mechanism in light and closed shell nuclides," Oak Ridge Linear Accelerator (1975), <http://www.nea.fr/dbforms/x4swdisp.cgi?30288.003>.
[25] Ibid.
[26] Kruger, "Delayed Fission," Fig. 4, based on measurements by R.E. Sund and R.B. Walton, "Gamma Rays from Short-Lived Fission Products Isomers," *Phys. Rev.* 86:824 (1966).
[27] Kruger, "Delayed Fission," Figs. 1 and 2, showing the gamma and beta spectra from fission at 2.2 seconds, based on J. K. Dickens et al., "Fission Product Energy Release for Times Following Thermal-Neutron Fission of Plutonium 239 and 241 between 2 and 14000 Seconds," *Nuc. Sc. Eng.* 78:126 (1981). Kruger and others have noted the spectrum does not change much with time. The dependence of the spectra on the energy of the fissioning neutron is also small.
[28] Kruger, "Delayed Fission," p. 4, based on the measurements by Dickens; see previous endnote.
[29] Kruger, "Delayed Fission," Figs. 7-10. Applying our rough estimation method for Case 1 to this case gives results of the same order of magnitude as Kruger's more careful calculation.
[30] Gary Stradling, private communication based on unclassified research. Classified research has also been conducted on bio-agent sterilization by heat and radiation.
[31] The heat conductivity for non-conducting solid or liquid materials is on the order of 0.1-1 watts per meter per Kelvin. See Walter Benenson et al., ed., *Handbook of Physics* (New York: Springer-Verlag, 2002), p. 794. The same reference gives specific heats and densities for the media of interest on the order of one to a few thousand joules per kilogram and thousand kilograms per cubic meter. Thus, the heat diffusion constant is on the order of 10^{-7} meters squared per second.
[32] Hans Kruger, personal communication.
[33] L.A. Glenn, private communication.
[34] Glasstone and Dolan, Chapter 5.
[35] Teller et al., p. 107.
[36] Frank Serduke, "Standard KDFOC4 Fallout Calculations for Buried Nuclear Detonations," UCRL-ID-146937, Lawrence Livermore National Laboratory (September 14, 2001).
[37] The LD50 dose is regarded as lethal to 50% of the exposed population.
[38] Another recent fallout estimate can be found in Nelson (2002), endnote 12, p. 12-15.
[39] See the discussion and figures in Teller et al., pp. 201-207. The focus in Teller et al. is on distances greater than those on which we focus, since they assume that the immediate surroundings of the explosion will be evacuated and controlled, as in the case of civilian uses of cratering explosions.
[40] Teller et al., Fig. 4.62, p. 209.
[41] C. W. Young, "Penetration Equations," Sandia National Laboratories (October 1997) and C. W. Young, "Depth Prediction for Earth–Penetrating Projectiles," *Journal of the Soil Mechanics and Foundations Division* SM 3:813 (May 1969).
[42] Young, "Penetration Equations," p. 10.
[43] Young, "Penetration Equations," p. 7.

[44] See Teller et al., pp. 132-133. There the Sedan vaporization radius is estimated at 10 meters for 100 kilotons. The vaporized mass is estimated at one-eighth the molten mass or 7500 tons for 100 kilotons. These numbers scale to about 2+ meters and 60-70+ tons for 1 kiloton.
[45] M. D. Nordyke, "Peaceful Uses of Nuclear Explosions," endnote 15, p. 54.