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Effectiveness of Nuclear Weapons against Buried Biological Agents

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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 bioagents are stored, on the location of the explosions with respect to the bunkers, the bioagent 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 bioagents 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. Based on preliminary calculations, casualties from the aboveground effects of underground nuclear explosions would be fewer than the casualties that would result from the dispersal of large quantities of bioagents.

INTRODUCTION

This report describes the results of some calculations and estimates made regarding the use of penetrating nuclear weapons against targets containing

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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 two 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 1970s. The second section describes the mechanisms by which a nuclear explosion can destroy bioagents buried underground, in bunkers and otherwise. The effectiveness of the nuclear explosions depends in detail the construction of the bunkers; on how the bioagents are stored; on the location of the explosions with respect to the bunkers, the bioagent 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 bioagents is derived from various unclassified sources.

The full version of this report includes a third section describing the aboveground effects of the nuclear explosions considered, all of which would vent to the surface.[1] These effects include intense local radioactivity, as well as significant fallout, air blast, and seismic activity to distances of kilometers. 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.

PHENOMENOLOGY OF UNDERGROUND NUCLEAR EXPLOSIONS

The rationale for using nuclear weapons against bioagent targets is that the expected heat and radiation could deactivate the bioagents and not just disperse them. This rationale applies to both surface and underground bioagents targets. The case of surface bioagent targets was treated, among others, by Hans Kruger[2] 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 bioagents 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 1970s,[3] 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.[4] A comprehensive summary of many data obtained in the Plowshare program is given in Teller et al., *The Constructive Uses of Nuclear Explosives*,[5] 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,[6] 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.[7] 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[8] 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.[9] 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[10] 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 bioorganisms 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 bioagents. The venting time determines the duration of the bioagents' 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 bioagents 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 bioagents.

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, and (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.[11]

We consider below cratering explosions with yields of 1 and 10 kilotons exploded at depths of 10 and 30 meters in desert alluvium (one set of results is for basalt). We also include some more qualitative remarks on granite and concrete. Granite is a high sound-speed competent rock, while alluvium is more representative of soils with much slower sound speed. 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.

We begin with some qualitative comments on penetration into rock. Data and calculations from Young et al.[12] 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.[13] Antoun, Lomov, and Glenn[14] 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[15] estimates a penetration of 12 meters for a 4-meter long projectile into concrete. Glenn[16] 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.

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.

Since nuclear explosions 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.

At the very early times (a few milliseconds) corresponding to maximum expected penetration into granite, calculations of the parameters relevant to bioagent 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, temperatures are in the thousands of kelvin briefly. Nonhydrodynamic energy transfers are still taking place.

For alluvium, we made estimates of venting times and cavity radii at that time based on interpolation and extrapolation to early times from Plowshare data and calculations (see Appendix 1). The amount of weapons material vaporized will be insignificant compared to the amount of rock/soil melted and vaporized. Estimates of the amount of ground material vaporized and melted can be made by scaling from data mainly from the Hardhat (for granite) and Sedan (for alluvium) events. These data also allow us to estimate the shock pressures at the maximum radius where vaporization takes place. From those pressures and the corresponding Hugoniot 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 1.

Table 2 applies 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

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

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[17] (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.

We could only make order of magnitude estimates of tonnes vaporized and melted, using energy conservation and data on peak stresses.

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 bioagents 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).[18] 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 bioagents, we note that, without specifying the construction and materials of the bunkers and the nature of the bioagents' 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 1.

All of the cases presented will create large craters with radii and depths varying from 20 to 80 meters depending on yield and ground material.[19] 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.

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

We show in Table 3 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 nonzero yield strengths so that the scalar pressures must be replaced by the stress tensor

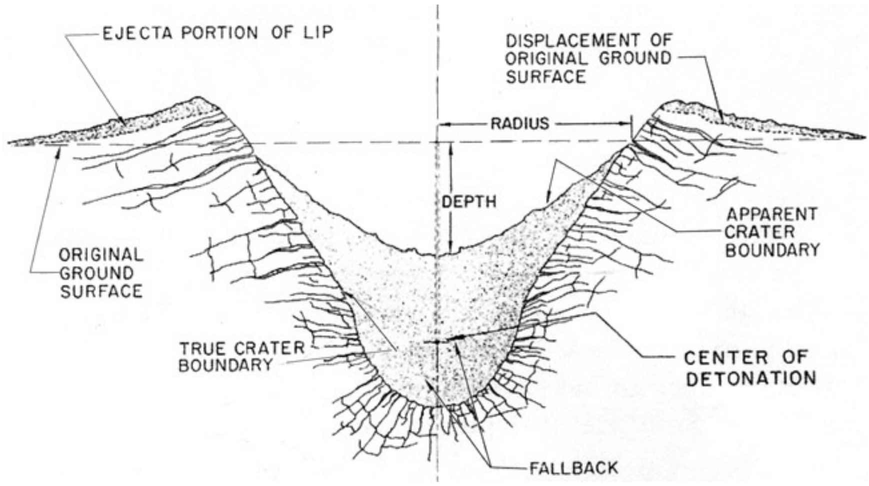

Figure 1: The typical shallow crater with a lip around its edge. *Source*: From Teller et al., *The Constructive Uses of Nuclear Explosives,* Fig. 4.49, p. 187 (McGraw-Hill Book Company, 1968).

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.

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.,[20] 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.

Table 3: 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.

DESTROYING BUNKERS AND DEACTIVATING BIOAGENTS

This section identifies the mechanisms that can destroy bioagents 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 bioagents, a distinction must be made between what destroys the bunker and what destroys the bioagents. 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 bioagents. A conservative but realistic criterion for destroying the bioagents themselves may thus be whether the explosion delivers enough heat and radiation to destroy the bioagents before they can vent to the surface. After venting, other effects such as atmospheric exposure and fallout might deactivate the escaped bioagents, but their effectiveness is more uncertain.

Deactivating Bioagents by Radiation and Heat

We turn to the destruction mechanisms for the bioagents and begin with radiation effects on bioagents. Bioagent 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.[21] The specific nature of the bioagents 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 bioagents 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 bioagents in solution. This case was examined in detail by Hans Kruger,[22] who posited a bunker 60 meters in length, 10 meters high, and 10 meters wide with walls made of 1-meter thick concrete, and with the top of the bunker 10 meters below the surface.[23] 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 bioagent 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 bioagents. 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 previously discussed in 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.[24] 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 bioagents that have clear lines-of-sight to the explosion. If the bioagents are in a liquid solution, as Kruger assumes (see note 21), 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 bioagents 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.[25] 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). An additional 10 MeV of gamma rays ($2.4*10^{18}$ ergs/kt) appear immediately at the site of the neutron capture[26] 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.[27] The total neutron cross section in the 1–2 MeV region on Si is 1–3 barns.[28] 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,[29] 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 bioagents 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.[30] Using a mean gamma energy of 0.5 MeV and a mean beta energy of 1.2 MeV[31] and a ratio of 3:2 gammas to betas/fission/second,[32] 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 bioagent 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 bioagents if the time available is on the order of 10 milliseconds, that is, 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, that is, 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 bioagent irradiated above the criterion quoted may be small compared to the total amount stored, depending on the fraction of the bioagents 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 bioagents 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 bioagent 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.[33] Over the first 10 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 bioagents 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 bioagents, whether vaporized or not, and the surrounding medium undergo complex motion. As the cavity vents to the surface and cratering takes place, whatever bioagents remain in the highly radioactive crater and lip are exposed to further radiation. In addition, ejected bioagents 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 bioagents 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 bioagents 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. If we assume this to be at least an hour, the irradiation time goes up by a factor of more than one million, so that the dose is now in the range of 20–100 megarads. 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 bioagents 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 bioagents 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 bioagents. 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 bioagents, but that may be comparable to, though not clearly larger than, the sterilizing dose. Finally, much or all of the bioagent 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 bioagents 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 bioagents are distributed in the debris and eventual fallout without much more detailed calculation and experimentation. In particular, it is likely that the bioagent 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 1). Data regarding the effectiveness of this exposure to heat of various specific bioagents 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.[34] Based on our estimated temperature and times, bioagents exposed to cavity temperatures will therefore be sterilized. What happens outside that time and space window, that is, 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 bioagents 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 bioagent 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 nonvaporized bioagents 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.[35] 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 bioagents. On the other hand, uncertainties regarding the disposition of bioagents in target locations and the position of the explosion with respect to the target will remain.

Deactivating Bioagents by Atmospheric Exposure

If any active bioagents 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 bioagents in the atmosphere. As noted earlier, the bioagents 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 bioagents, but also any effect from the long-time exposure to the fallout radiation. We have no data regarding the fate of the bioagents mixed in with the radioactive cloud.

Preliminary calculations by Hans Kruger[36] 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 bioagents 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 bioagents 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. Bioagents 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 3 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.[37] 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.[38] 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.

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 bioagents 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 bioagents 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 bioagents 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 bioagent sterilization, so that any remaining active agents could be dispersed aboveground. Deeply buried targets will likely escape effective bioagent sterilization.
4. The spread of any remaining live bioagents 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 bioagents 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 bioagents 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 bioagents and their storage media, and the local atmospheric conditions.

NOTES AND REFERENCES

1. The full version of this report contains further descriptions and details (including calculations and diagrams) of various qualitative and quantitative aspects of using penetrating nuclear weapons against buried bioagent targets. We have noted where significant material has been omitted from this condensed version. The full report is available

at http://www.princeton.edu/~globsec/publications/SciGloSec.shtml (March 2004) and at http://cisac.stanford.edu (March 2004).

2. Hans Kruger, "Radiation Neutralization of Stored Biological Warfare Agents with Low-Yield Nuclear Warheads," UCRL-ID-140193, Lawrence Livermore National Laboratory (August 21, 2000).

3. Lawrence Radiation Laboratory et al., *Proceedings of the Third Plowshare Symposium, Engineering with Nuclear Explosives* (Berkeley: University of California Press, 1964).

4. 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.

5. Teller et al., *The Constructive Uses of Nuclear Explosives* (New York: McGraw-Hill Book Company, 1968).

6. Ibid., p. 129.

7. Ibid., p. 132.

8. 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.

9. Milo D. Nordyke, "On Cratering: A Brief History, Analysis, and Theory of Cratering," UCRL-6578, Lawrence Livermore National Laboratory (1961).

10. 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.

11. For details on cavity radius and venting time, including methods and diagrams, refer to the full version of this report.

12. 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).

13. An example is given in the full version of this report.

14. T. H. Antoun, I. M. Lomov, and L. A. Glenn, "Simulation of the Penetration of a Sequence of Bombs Into Granite," UCRL-JC-150778, Lawrence Livermore National Laboratory (November 12, 2002). The authors are indebted to Dr. Lew Glenn for many helpful comments and criticisms.

15. Robert Nelson, "Low-Yield Earth-Penetrating Nuclear Weapons," *Science & Global Security* 10 (2002).

16. Lew Glenn, private communication.

17. Teller et al., Fig. 4.40, p. 177.

18. 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 on discussions with Prof. Robert Tatum of Stanford University, to whom we are grateful.

19. More details are given in *Peaceful Nuclear Explosions* (see previous endnote) as well as in Teller et al. Some examples of crater parameters and volumes of broken rock are given in the full version of this report.

20. Teller et al., Fig. 4.32, p. 171.

21. Hans Kruger, "Delayed Fission Debris Radiation Effect on Chemical and Biological Agents Stored in a Bunker," UCRL-130475, Lawrence Livermore National Laboratory (1998).

22. Ibid.

23. 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, multiroom bunkers also exist. Our results do not depend on the amount of material stored in the bunker.

24. See Table 6 in Department of Energy, Nuclear Physics and Reactor Theory Handbook (1993), http://www.tpub.com/doenuclearphys/nuclearphysics31.htm (31 March 2004).

25. Ibid.

26. Ibid.

27. 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.

28. 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.

29. Ibid.

30. 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).

31. 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.

32. Kruger, "Delayed Fission," p. 4, based on the measurements by Dickens; see previous note.

33. 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.

34. Gary Stradling, private communication based on unclassified research. Classified research has also been conducted on bioagent sterilization by heat and radiation.

35. The heat conductivity for nonconducting 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.

36. Hans Kruger, personal communication.

37. L. A. Glenn, private communication.

38. Glasstone and Dolan, Chapter 5.

39. 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.

40. M. D. Nordyke, "Peaceful Uses of Nuclear Explosions," endnote 18, p. 54.

Appendix 1. 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. Figures 4.25 and 4.26, and for alluvium in Figure 4.32, supplemented in the case of alluvium by the estimates of vaporization mass and radius for Sedan.[39] 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 Hugoniot 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., Figure 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 nonuniformity.

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, $TV^\wedge(\gamma - 1) =$ constant. Teller et al. assume $\gamma = 4/3$ (Teller et al., p. 136). Nordyke[40] 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.