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Low-Yield Earth-Penetrating Nuclear Weapons

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Some senior members of the U.S. government and leaders of America's nuclear weapons labs have recently advocated that the U.S.A. develop a new generation of low-yield earth-penetrating nuclear weapons (EPWs) capable of destroying hardened and deeply buried targets. Because they are intended to detonate below ground and have substantially lower yields than typical weapons in the U.S. nuclear stockpile, it is often assumed that EPWs would produce "minimal collateral damage" and could even be used near densely populated areas.

We show here that EPWs cannot penetrate deeply enough to contain the nuclear explosion and will necessarily produce an especially intense and deadly radioactive fallout. A missile made of the hardest steels cannot survive the severe ground impact stresses at velocities greater than about $v_{max} \sim 1$ km/s without destroying itself. This limits the maximum possible penetration depth into reinforced concrete to about four times the missile length—approximately 12 meters for a missile three meters long. Underground nuclear explosions must be carefully sealed at depths greater than 90 $\mathrm{KT}^{1/3}$ meters (KT is the yield in kilotons) to be fully contained. At minimum, an earth penetrator creates an open crater or shaft, allowing release of hot plasma and radioactive material in a "roman candle" type explosion. An EPW would most likely excavate a crater of apparent radius $R_a \sim 50\ \mathrm{KT}^{1/3}$ m, throwing out a large amount of radioactive dirt and debris. A one kiloton earth-penetrating "mininuke" used in a typical third-world urban environment would spread a lethal dose of radioactive fallout over several square kilometers, resulting in tens of thousands of civilian fatalities.

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An increasingly vocal group of U.S. politicians and leaders of America's weapon laboratories are urging the U.S. to develop a new generation of precision low-yield nuclear weapons—"mininukes," with equivalent yields of a few kilotons of TNT or less.[1,2] Small nuclear weapons are necessary, they argue, to destroy hardened underground command bunkers and storage sites for chemical or biological weapons. While conventional earth-penetrating "bunker busters" are capable of destroying shallow-buried "cut-and-cover" structures at depths less than 10 meters below the surface, nuclear weapons are needed to destroy a "hardened and deeply buried target"—facilities having an overburden equivalent of 30 to 100 meters of reinforced concrete.[3,4]

The large yields of nuclear weapons currently in the U.S. stockpile—typically greater than 100 KT—would be so devastating to any civilian population, however, that no American president could contemplate their use. By adding low-yield nuclear weapons with earth-penetrating capability to the stockpile, mininuke proponents believe the U.S. would be able destroy these hardened targets while "limiting collateral damage."[5] As one Pentagon official put it to the *Washington Post* in spring 2000, "What's needed now is something that can threaten a bunker tunneled under 300 meters of granite without killing the surrounding civilian population."[6]

In this article, we demonstrate that the goal of a benign earth-penetrating nuclear weapon is physically impossible. We answer some obvious technical questions which have been previously missing from the debate: How deep can an earth penetrator burrow into the ground? Can it destroy a hardened bunker covered by 30–100 m of reinforced concrete? Will the nuclear explosion be contained, or will it produce radioactive fallout and other destructive effects?

Even if it could penetrate to great depth, an EPW would create an open crater or shaft that would allow release of hot plasma and radiation products from the nuclear explosion. To appreciate the effect, we can appeal to the very first underground nuclear test, named Pascal-A, which occured on 26 July 1957 in an unstemmed, open shaft one meter in diameter and 150 meters deep. Pascal-A was intended as a safety test, with a predicted yield of only 1–2 lb of TNT. Its actual nuclear yield turned out to be about 55 tons—55,000 times greater than expected—catching everyone off guard. Physicists Robert Campbell and Robert Brownlee provided a first hand account:

> Brownlee: It was the world's finest Roman candle, because at night it was all visible. Blue fire shot hundreds of feet in the air. Everybody was down in the area, and they all jumped in their cars and drove like crazy.
> Campbell: They were damn lucky they didn't go right through that [fallout] cloud. . . . bad as it was, spectacular as it was, there was only a tenth of the radiation on

> the ground around there that there would have been if it had been done on the surface.[7]

Additional nuclear explosions in unstemmed shafts typically released 5–10% of their total fission products into the local environment.[8]

We describe in the next section how earth penetration of only a few meters increases the underground destructive power of a nuclear explosion by more than an order of magnitude. There seems to be widespread confusion between this effect and the very deep earth penetration which would be requried for an appreciable containment. We then show that the maximum possible penetration depth in hardened concrete is limited to about four times the length of the missile. The burial depth required to contain a nuclear explosion, however, is very much larger. No EPW can penetrate a hardened site to the depths necessary to contain an explosion even as small as 0.1 KT. The missile will destroy itself from the intense impact stresses well before it could reach the depths required for nuclear containment. In a section on fallout, we describe the radioactive fallout produced in a shallow buried explosion, and estimate the fatalities expected if used in a densely populated area.

We find that the use of any nuclear weapon capable of destroying a buried target, one otherwise immune to conventional attack, will necessarily produce enormous numbers of civilian casualties if used near an urban environment. The explosion simply blows out a massive crater of radioactive debris, which rains down on the local region with an especially intense and deadly fallout.

WHY EARTH PENETRATION?

Using an above-ground nuclear explosion is actually a crude way to destroy a buried structure, like a hardened command bunker or a missile silo. Because the ground is nearly-rigid, most of the air shock energy from an above-ground nuclear burst is reflected back into the atmosphere; the large density contrast between the air and ground creates a mechanical "impedance mismatch," and only a small fraction of the total energy is transmitted into the ground. Several meters of dirt will protect most hardened structures from all but the highest-yield weapons. Consequently, until recently the 9-Megaton B53 warhead was required to destroy hardened underground targets like Soviet command and control bunkers.

A nuclear explosion which is buried by only a few meters, on the other hand, produces a much more intense and damaging seismic shock than an air burst of the same yield. The dramatic change in the "equivalent yield" of the weapon with burial depth is shown in Figure 1. Less than one meter of burial increases

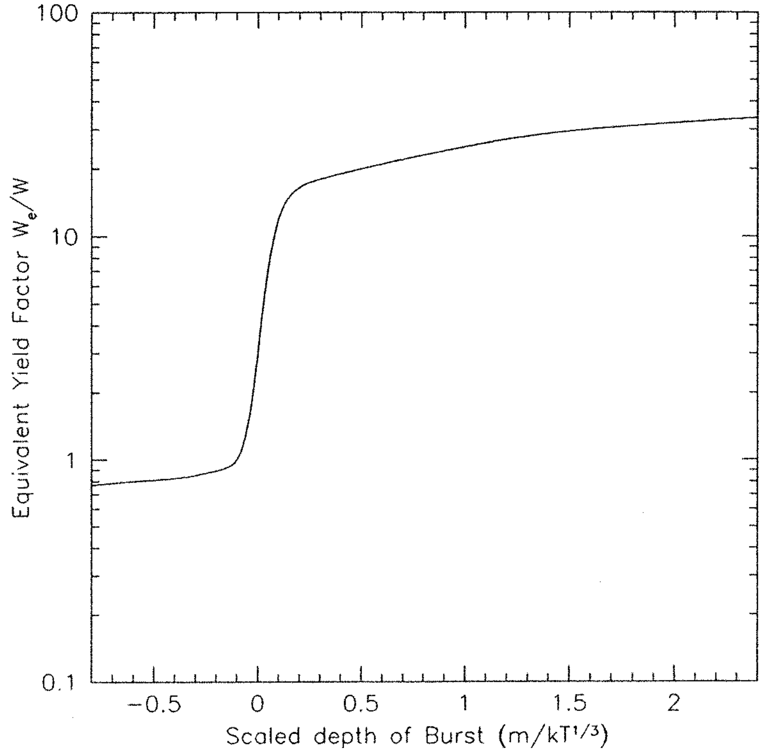

Figure 1: The Equivalent Yield Factor as a function of scaled Depth of Burst. Only a few meters of burial enhances energy coupling by more than an order of magnitude. Data are from DWSA Effects Manual EM-1 1990.[26]

the energy coupling by more than an order of magnitude. The warhead is thus more likely to destroy a buried hardened structure if it first penetrates into the ground near the target before detonating.

The U.S. replaced the aging B53 in 1997, by putting the nuclear explosive from an earlier B61 bomb design into a hardened steel casing with a new nose cone to provide ground penetration capability. This B61-11 has a variable yield of 0.3–300 KT. Its earth-penetrating capability is quite modest, however. In two drop tests from approximately 2.5 km (40,000 ft) near Fairbanks, Alaska an unarmed B61-11 penetrated into frozen tundra only 2–3 meters. Even so, by burying itself into the ground before detonation, a much higher proportion of the explosion energy would be transferred to ground shock compared to a surface bursts, making it at 300 KT the equivalent of a 9,000 KT surface burst. Because the B61-11 is much lighter than the 8900 pound B53, it can be delivered by the stealthier B-2A bomber, or even an F-16 fighter, instead of the the vulnerable

B-52 required of the B53. It also has modern safety and security features lacking in the B53. And it has less fallout, but still that of a surface burst.

Limits of High-Velocity Kinetic Penetration

The B61-11 drop tests described above were limited to terminal impact velocities $v \lesssim 300$ m/s. In principle, the 2–3 m penetration depths would increase if the weapon was fitted with a propulsion system that could provide higher impact velocities. However, a missile cannot penetrate to arbitrarily large depths simply by increasing its impact velocity. To explain this point we can do no better than to quote George Ullrich, the civilian deputy director of the Defense Special Weapons Agency:

> There is a limit to how deep you can get with a conventional unitary penetrator. . . . fundamentally, you're not going to come up with a magic solution to get 100 feet or deeper in rock. If you go to higher velocities you reach a fundamental material limit where . . . the penetrator will eat itself up in the process, and in fact that will achieve less penetration than at lower velocity. So you get into these different regimes where you are really just fundamentally limited, physically, in how deep you can get into rock.[3]

As we show below, the goal of 100 feet penetration, quoted above, is almost certainly too optimistic.

The penetration depth and crater formation of a missile impacting a solid target depends on the mechanical response of both the target and penetrator at high dynamic stress levels. Theoretical formulae can be derived by assuming that the target material behaves like an ideal elastic-plastic solid, and this works well for metal armored plating, or penetration into clays and soils.[10,11] However, hardened targets, by definition, are constructed with reinforced concrete or mined out of solid rock. These materials are brittle and tend to fracture upon kinetic impact, and theoretical understanding is limited. It is generally accepted that empirically based formulae are more accurate.

Bulson[11] reviews a variety of empirically determined concrete penetration formulae. He concludes that most accurate results are based on extensive range of wartime data by the British Road Research Laboratory. Writing the ratio of penetrator mass to cross sectional area in terms of the mean density and length, $M/A = \rho_p L$, and converting to MKS units, the result for the penetration depth D can be expressed as

$$\frac{D}{L} = 2.0 \left(\frac{\rho_p}{10^3\,\mathrm{kg/m^3}} \right) \left(\frac{\mathrm{MPa}}{Y_t} \right)^{1/2} \left(\frac{v}{533\,\mathrm{m/s}} \right)^{n}, \qquad (1)$$

where $n = 3.1\,(Y_t/\mathrm{MPa})^{-1/4}$, and Y_t is the unconstrained compressive strength of the target. Here MPa stands for megapascals, 10^6 Pa. In the U.S.A., an extensive dataset developed at Sandia Laboratories, has resulted in empirical formulae summarized by[12]: for $v \gtrsim 60$ m/s,

$$\frac{D}{L} = 1.3N\left(\frac{\rho_p}{10^3\,\mathrm{kg/m^3}}\right)\left(1-\frac{Y_t-14}{115\,\mathrm{MPa}}\right)^2\left(\frac{v-30}{1000\,\mathrm{m/s}}\right), \tag{2}$$

where $N = 0.56 - 1.34$ accounts for variations in the missile nose shape, from flat to conical. These formulae are only valid at impact velocities where the missile can be treated as a rigid penetrator of constant length. The missile will plastically yield or erode when the impact ram pressure approaches the finite yield strength of the missile casing $\rho_t v_p^2/2 \gtrsim Y_p$. Consequently, the impact velocity must be less than

$$v_{max} = \left(\frac{2Y_p}{\rho_t}\right)^{1/2} = 1\frac{\mathrm{km}}{\mathrm{s}}\left(\frac{Y_p}{10^3\,\mathrm{MPa}}\right)^{1/2}\left(\frac{2\ 10^3\,\mathrm{kg/m^3}}{\rho_t}\right)^{1/2}. \tag{3}$$

Experimental data for hard steel penetrators impacting concrete at high velocity are shown in Figure 2, along with the penetration curves predicted by equations (1) and (2). The particular type of concrete used in the experiment is unknown, but we have assumed it has an unconstrained yield strength in the middle of the range given in Table 1 ($Y_t = 50$ MPa). Here the 0.22 m missiles are able to penetrate at most about 4.3 times their length (0.95 m). The peak penetration occurs near the predicted maximum velocity, $v_{max} = (2Y_p/\rho_t)^{1/2} = 913$ m/s, using the parameters in Table 1. At this velocity, the projectiles showed severe erosion, while at 1200 m/s the missile suffered extreme plastic deformation and fractured into multiple pieces.[13]

In practical scenarios, the actual vertical penetration depth will be substantially less than predicted by Eqs. (1) and (2) at $v = v_{max}$. First, in order to ensure the missile is not damaged before detonation, impact velocities must

Table 1: The density ρ and dynamic strength Y of various materials (All values are approximate and depend on the specific type of material. Note the conversion factors: 1 gm-cm^{-3} = 10^3 kg/m^3, 1 MPa = 10^6 Pa = 145 psi).

Material properties

Material	Density (10^3 kg/m^3)	Yield (MPa)
Soft rock	1.5–2	30
Reinforced concrete	2.5	30–100
Hard rock	2.5	300
E4340 steel	8	1000

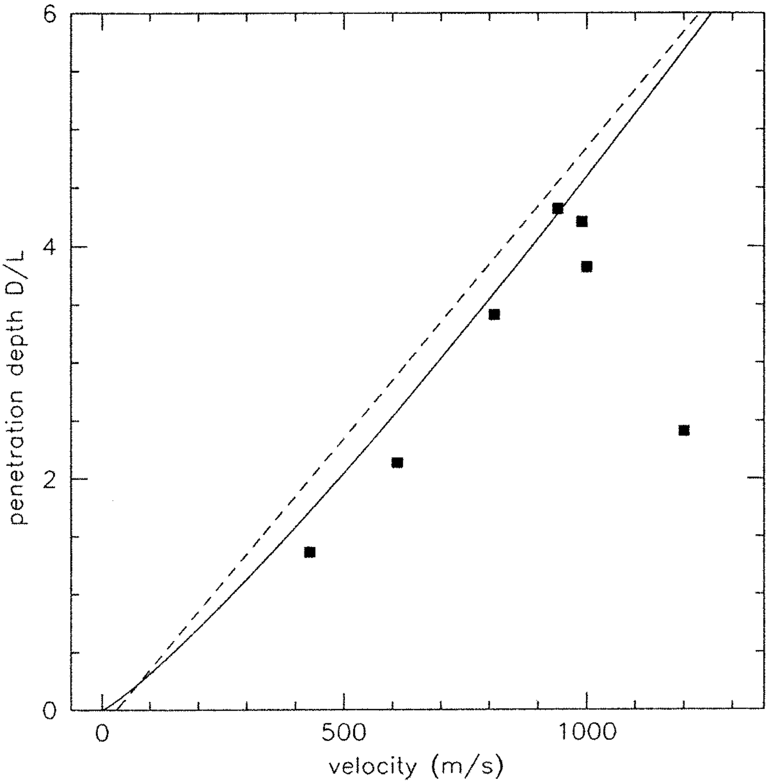

Figure 2: Penetration depth versus striking velocity for E4340 steel projectiles into concrete. The curves correspond to equation (1) (solid) and equation (2) (dashed). The solid squares are experimental data for $L = 0.22$ m solid steel projectiles.[13] The strength of the concrete target is unknown, but we have used $Y = 50$ MPa—the middle of the range in Table 1—as a characteristic example. These projectiles show severe erosion at impact velocities above 900 m/s, very close to the predicted critical yield velocity $v_{max} = (2Y_p/\rho_t)^{1/2} = 913$ m/s using the data from Table 1. At $v = 1200$ m/s the missile suffered extreme deformation and fractured into multiple pieces.

be substantially less than the maximum velocity given in Eq. (3). The velocity may also need to be decreased in order to reduce the tremendous deceleration at impact; at $v = v_{max}$ the magnitude of the deceleration is

$$\frac{a_{max}}{g} = \frac{AY_p}{M_p g} \simeq 10^5 \left(\frac{A}{0.1\,\mathrm{m}^2}\right)\left(\frac{Y_p}{10^3\,\mathrm{MPa}}\right)\left(\frac{10^3\,\mathrm{kg}}{M_p}\right), \tag{4}$$

where $g = 9.8$ m-s^{-2} is the acceleration of gravity. This is more than an order of magnitude larger than the high accelerations experienced by nuclear artillery shells.[14] Most projectiles will also impact the ground at an angle, θ, away from the normal, so that it has a horizontal velocity component $v_h = v_p \sin\theta$. The corresponding vertical penetration depth will be reduced at least a factor $\cos\theta$, and possibly more, because aerial bombs at high obliquity tend to follow a J-shaped penetration path, curving forward in the direction of the horizontal velocity.[11] Finally, because the missile is not solid metal, its mean density will be somewhat less than that for a solid steel missile assumed here.

We thus conclude that no EPW can penetrate reinforced concrete deeper than four times the length of the missile—about 12 meters for a missile three meters long. The most successful conventional penetrating weapon, the GBU-28, is advertised to have a penetrating capability of about six meters of concrete.[3]

UNDERGROUND NUCLEAR EXPLOSIONS

Although the destructive power and probability of destroying a buried and hardened target is greatly increased by burrowing the weapon into the ground, a nuclear explosion buried only a few tens of meters below ground will not be contained. A buried nuclear explosion initially vaporizes the local rock, producing a high temperature plasma-filled cavity with an initial pressure of several million atmospheres—many orders of magnitude greater than the overburden pressure due to the overlying earth or rock, or even the strength of the rock. The cavity expands rapidly, sending a strong compressional seismic shock wave outward. If the explosion occurs sufficiently close to the surface, the explosion blows out a crater of dirt and debris.

The required depth of burial to fully contain an underground nuclear explosion depends upon the strength, porosity and sealing nature of the rock (or soil), as well as the location of the water table. At the Nevada Test Site (NTS), explosions must be buried deeper than an empirically determined minimum depth,

$$D \gtrsim 92 \ \ \mathrm{KT}^{1/3}\mathrm{m}, \tag{5}$$

or (300 $\mathrm{KT}^{1/3}$ feet)—where the top of the “chimney” lies just below the surface.[16] In practice, many tests at depths near this minimum depth have leaked radioactivity and carefully sealed shafts have ruptured. This led to an additional safety factor. All tests at the NTS are buried at depths $D = 122\ \mathrm{KT}^{1/3}$ m.[8] For media with substantial water content, even deeper burial is recommended. Furthermore, no tests are conducted at less than 185 m (600 ft). The required containment depth is only weakly sensitive to the weapon yield. Weapons with

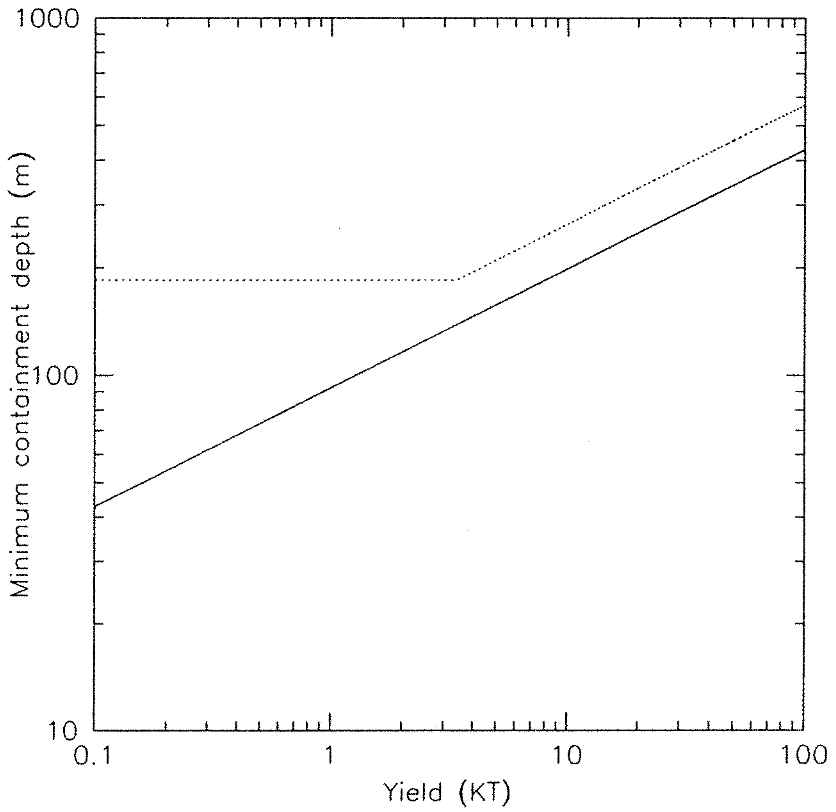

Figure 3: Minimum depth of burial (solid line) required to contain an underground nuclear explosion. A more restrictive criterion (dashed line) is actually used at the U.S. Nevada Test Site.

yields as small as 0.1 KT still would have to be buried at a depth $D \gtrsim 43$ meters (140 ft) in order to be fully contained. The minimum depth of burial required to contain a nuclear explosion at NTS is shown in Figure 3 as a function of nuclear yield.

Cratering Explosions: The Plowshare Tests

Much of our knowledge of shallow buried nuclear explosions comes from the Plowshare series of nuclear tests. These were originally intended to develop a capability to use nuclear explosions for large excavation projects, such as building canals or new ports. They were thus buried at fairly shallow depths and optimized to produce large craters. The yield and depth of each Plowshare test along with the resulting crater dimensions are given in Table 2.

Table 2: Data from Plowshares excavation experiments[20,28,29] (Note that even very low-yield explosions produce substantial craters. F_C is the fraction of gamma activity produced by the fission yield and appearing in the close-in fallout. F_C is normalized to 3380 rad/hr per kiloton of fission yield per square mile at one hour after detonation, with a terrain shielding factor of 0.8).

Plowshares cratering explosions				
Event	**Yield (KT)**	**Burial depth (m)**	**Crater radius (m)**	**Activity fraction F_C**
Danny Boy	0.43	34	33	0.04
Sedan	104	195	188	0.1
Palanquin	4.3	82	37	—
Cabriolet	2.3	53	56	—
Schooner	35	109	131	—
Teapot ESS	67	34	45	0.46
Neptune	0.1	30	31	0.005
Jangle U	1.2	5.2	80	0.64
Jangle S	1.2	0	—	0.5
Blanca	19	257		0.0005

A nuclear explosion occuring at depths less than required for containment produces a crater. The size of the crater depends sensitively on the depth of detonation, the type of soil or rock, and the depth of the local water table. The volume of the apparent crater produced by a buried nuclear explosion is shown in Figure 4. A one kiloton weapon detonated at a depth of 30 meters in dry soil or soft rock will produce a crater with an apparent radius $R_a \approx 55$ meters—more than a football field in diameter—and with an extended lip of ejecta two to three times this radius.[16] Between 10 to 50% of the total mass ejected from the crater settles as local radioactive fallout.

When bored through solid rock, underground structures are fairly resistant to ground shock.[16] The rock, being an elastic medium, will transmit the pressure wave. Damage occurs primarily through spalling—tensile failure as the shock reflects at an air-wall interface. For low-yield weapons, it is difficult to produce significant damage to a buried structure unless it is within the rupture zone, a region near the crater where the shock is sufficiently strong to plastically deform and crush the rock. Glasstone[16] gives damage criteria for moderately deep underground structures. Severe damage leading to collapse occurs only for structures within $1.25R_a \approx 70$ KT$^{1/3}$, assuming the weapon is buried at the optimum scaled radius of 30 KT$^{1/3}$ meters. A warhead with a yield $\gtrsim$3 KT would thus be required destroy a structure buried as deep as 100 m. However, this explosion would not be contained. It would produce a crater nearly 80 meters in radius and 30 meters deep. Higher yields would be necessary for penetration depths less than the optimum for crater formation.

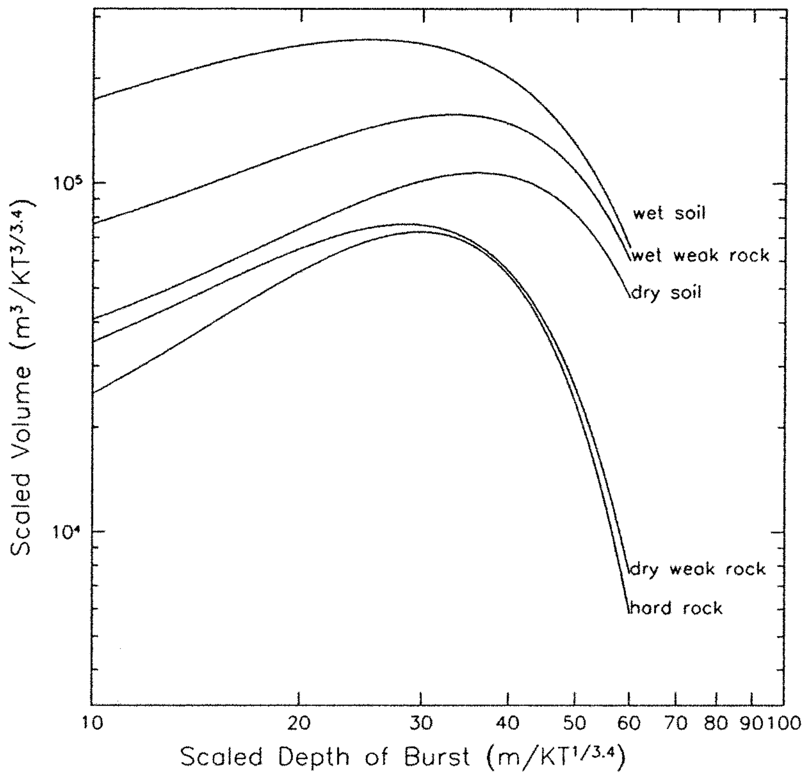

Figure 4: Scaled volume of the *apparent* crater produced by a buried nuclear explosion as a function of the scaled depth of burst $D/KT^{1/3.4}$. The craters are largest in soil or weak wet rock, and peak at scaled depths of 30–40 m/$KT^{1/3.427}$. The diameter and depth of the crater are related to the apparent volume by $R_a = 1.2V_a^{1/3}$ and $D = 0.5V_a^{1/3}$. A 1 kiloton explosion detonated at a depth of 30 m would produce a crater of radius $R_a \approx 55$ m —more than a football field in diameter.

FALLOUT FROM A SHALLOW BURIED NUCLEAR BLAST

Surface and shallow buried nuclear explosions produce much more intense local radioactive fallout than an equivalent-yield high-altitude burst, where the fireball does not touch the ground.[17] When the fireball breaks through the surface of the earth, it carries with it into the air large amounts of dirt and debris. In addition to the radioactive fission products from the weapon itself, this material contains nuclei made radioactive by the large number of neutrons produced from the nuclear detonation. The resulting radioactive dust cloud does not rise as high as a classic mushroom cloud, but typically consists of a narrow column of vented hot gas surrounded by a broad base surge of ejecta and suspended fine particles.

The spatial distribution of radiation is sensitive to a number of parameters: the depth of burial, the type and moisture content of the soil or rock, the local wind speed and precipitation, and the local terrain. Consequently, quantitative estimates of fallout and radiation dose are necessarily crude. Nevertheless, we can use actual fallout data measured in the Plowshare series of shallow-buried nuclear tests carried out in the early 1960s.[18,19] The fallout cloud from the 2.3 KT Cabriolet Plowshare test is shown in Figure 5. The device was buried at a depth of 52 meters. The highly radioactive base surge cloud reached a diameter of approximately 2.5 km.

Approximate scaling laws for the height and diameter of the base surge cloud can be taken from Figure 6.10 of Reference 18,

$$H_B \approx 570\,\mathrm{KT}^{0.2}\ \mathrm{m}, \qquad R_B \approx 1\,\mathrm{KT}^{0.3}\ \mathrm{km}. \tag{6}$$

These are based on Plowshare tests detonated at scaled depth $\sim$46 $\mathrm{KT}^{1/3}$ m, optimized to produce the largest crater.

We can estimate the characteristic fallout velocity v and deposition time (t_v) by equating the gravitational force to the Stokes drag force, $mg = 6\pi\eta va$,

Figure 5: The 2.3 kiloton Cabriolet Plowshare test was buried at a depth of 52 meters. It produced a crater 36 m deep and 110 m in diameter. The highly radioactive base surge reached a diameter of approximately 2.5 km.[20]

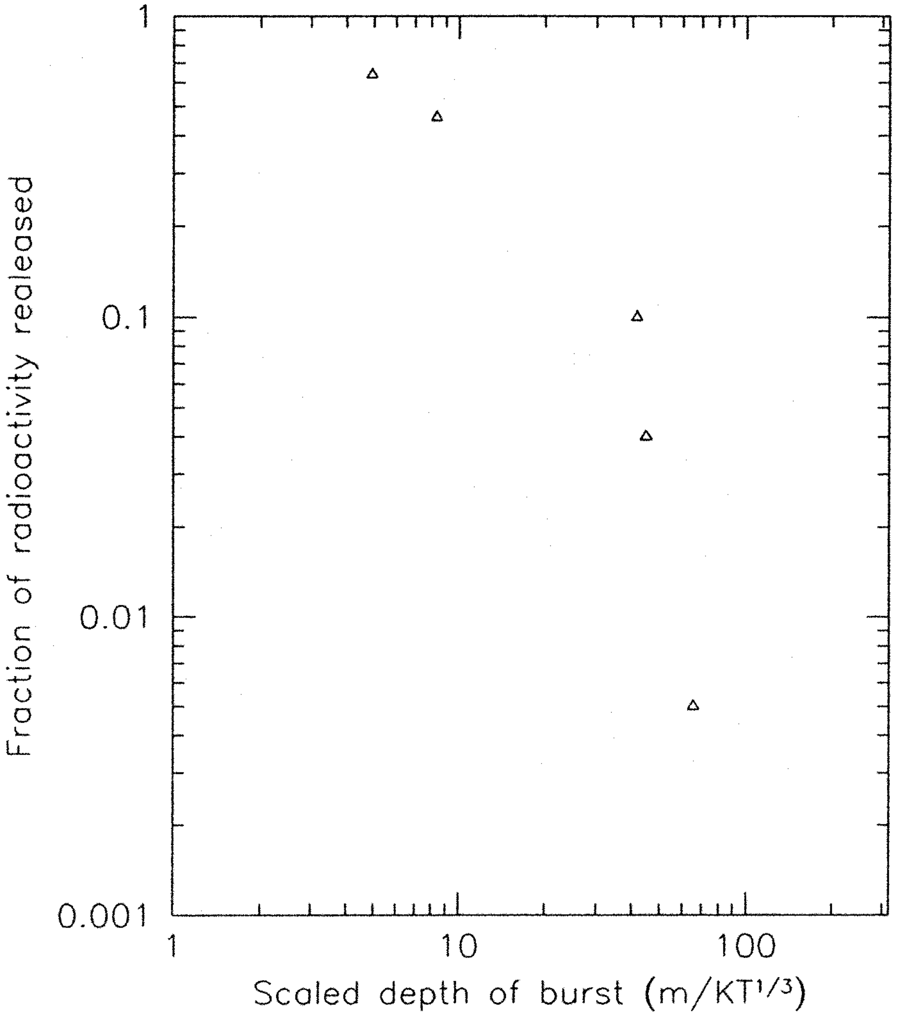

Figure 6: The fraction F_C of total radioactivity produced that contributes to local fallout gamma dose as a function of scaled depth of burst from Table 2. F_C is normalized to 3380 r/hr per kiloton of fission yield per square mile at H + 1 hr, with a terrain shielding factor of 0.8.[20,28,29]

acting on a spherical particle of radius a, mass $m = \pi a^3 \rho/3$, falling through air with a fluid viscosity $\eta = 1.82 \times 10^{-5}$ Pa-s,

$$v = \frac{2}{9}\frac{a^2 \rho g}{\eta} \simeq 3\left(\frac{a}{100\mu}\right)^2 \text{ m/s}, \tag{7}$$

where we use $\rho = 2.5$ gm-cm^{-3} as a characteristic soil particle density. Surface and subsurface explosions generate fallout particles of dirt and debris which are larger than for high altitude bursts. These particles will thus fall out and be deposited on the ground on a time scale

$$t_d \sim \frac{H_B}{v} \approx 190\,\mathrm{KT}^{0.2}\left(\frac{a}{100\mu}\right)^{-2}\ \mathrm{s}. \tag{8}$$

Particles of size 10–100μ will thus fall out in a few minutes to hours, much shorter than for a higher altitude explosion. This results in almost immediate exposure to a high radiation field for people living within a few kilometers of the explosion, even for relatively low-yield weapons.

The radioactivity is due to the decay of a large number of radionuclides. To a good approximation, the local dose rate decays as a power law in time,

$$R = R_1(x, y)t^{-1.2}, \tag{9}$$

where R_1 is the total gamma radiation dose rate at unit time (usually 1 hour) after the explosion.[16] This power-law approximation is valid for times from a few minutes to up to six months. The value of the one-hour dose rate R_1 will depend on the distance from the burst, the local terrain, weather conditions, and so on. Isodose contours for the 0.43 KT plowshare test "Danny Boy" are shown in Figure 7. The burial depth of 34 m—a scaled depth of 45 m—reduced the fraction of total radioactivity released to $F_c = 0.04$.

We can crudely represent the fallout pattern as a Gaussian with a characteristic radius equal to the radius of the base surge cloud, Eq. (6)

$$R_1 = R_c e^{-r^2/R_B^2}. \tag{10}$$

J. B. Knox[20] expresses the total activity of the Plowshare tests in terms of the area integral,[21]

$$AI = \int R_1 dA = 3380 F_c\ \mathrm{miles}^2\ \mathrm{rads/hr\,KT}, \tag{11}$$

where F_c, the fraction of total radioactivity produced in the explosion that contributes to local fallout, is given in Table 2 and Figure 7. If the radioactive material from a one kiloton weapon detonated at the surface ($F_c = 1$) were spread evenly over an area of one square mile, then the dose rate would be 3380 rad/hr. Using Eq. (10) in the integral, we find

$$R_c = \frac{F_c AI}{\pi L_B^2} \approx 2800 F_c\,\mathrm{KT}^{0.5}\mathrm{rad/hr}. \tag{12}$$

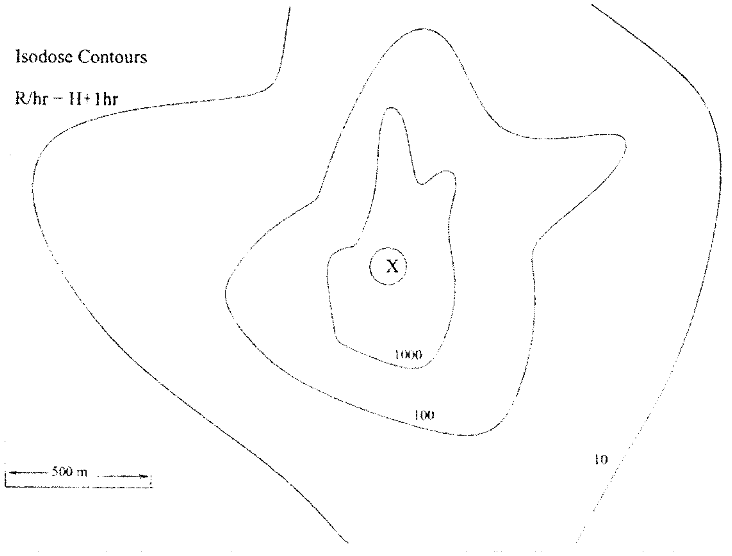

Figure 7: Approximate H + 1 hour isodose contours due to fallout from 0.43 KT "Danny Boy" Plowshare test. The burial depth of 34 m—a scaled depth of 45 m—reduced the fraction of total radioactivity released to $F_C = 0.04$. Roughly everyone within 100 rad H + 1 hr contour would receive a fatal dose of radiation if they are not quickly evacuated.[30]

Estimated Casualties from an Earth-Penetrating Weapon

Casualties from an earth-penetrating nuclear weapon will be due primarily to ionizing radiation from local fallout. The total dose between the fallout deposition time t_d and evacuation time t_e is then

$$D = \int_{t_d}^{t_e} R\,dt = 5R_1\left(t_f^{-0.2} - t_e^{-0.2}\right) \equiv R_1 f. \tag{13}$$

The value of f depends on the choice of deposition and evacuation times. For $t_d = 0.5$ hour, and $t_e = 3$ hours, $f = 1.7$, while for $t_d = 0.1$ and $t_e = 12$ hours, $f = 4.9$. The integrated radiative dose as a function of time is plotted in Figure 8. Note that most of the integrated exposure will come from the first few hours. This leaves little time for evacuation.

Serious illness begins to occur at total dosages between 100–200 rads. Official U.S. estimates assume that a 450-rad residual dose would cause a 50% fatality rate from radiation sickness within 60 days (LD-50 = 450 rads). However, it is generally thought that the synergistic effects of the radiation doses with other traumas and stresses associated with the nuclear explosion and

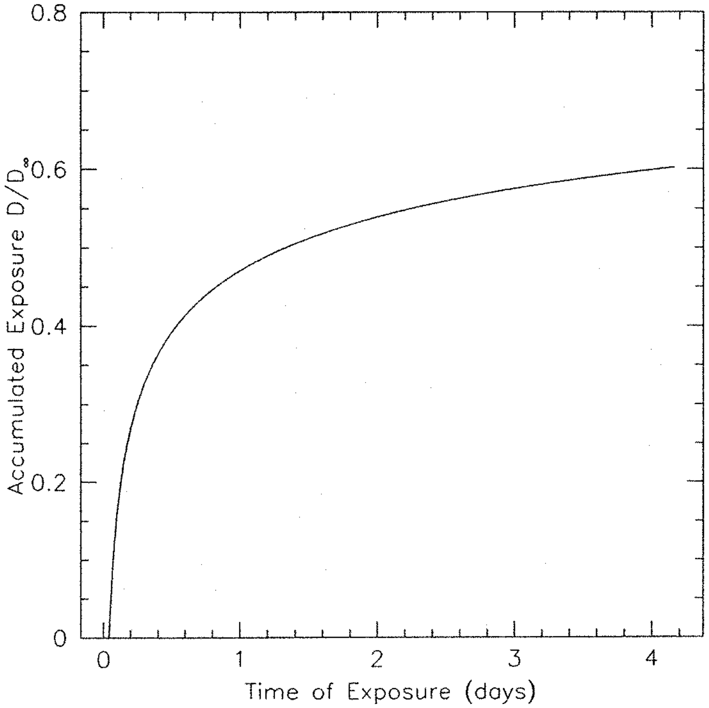

Figure 8: The total radiative dose as a function time since deposition (Eq. 13). Most of the cumulative dose occurs within the first 24 hours, before the bulk of any urban population could evacuate.

its aftermath reduce this value, so that LD-50 is somewhere between 250–450 rads; the corresponding 100% fatal dose, in the absence of intensive hospital care, varies from $D_1 \sim 400$–600 rads.[22] Fatalities from radiation exposure will thus be 100% inside a 1-hour isodose contour of magnitude $R_1 = D_1/f \sim 100$–200 rad, for an evacuation time of $t_e \sim 3$ hr.

The lethality function, $L(D)$, determines the fraction of deaths occuring in a population exposed to a total radiative dose D. Above some maximum dose $D > D_1$ fatality is certain, so $L = 1$, while below a minimum dose $D < D_0$ there are no short-term deaths so that $L = 0$. We approximate the lethality fraction as linear between these two extremes,

$$L(D) = \frac{D - D_0}{D_1 - D_0}, \qquad D_0 < D < D_1 \tag{14}$$

The 50% fatality rate occurs at a dosage $D_{50} = (D_0 + D_1)/2$.

The total number of expected fatalities is just the lethal dose fraction times the population density σ integrated over the area,

$$N = \int L\,[D(r)]\,\sigma\,(r)dA, \tag{15}$$

and $L(D)$ is the lethal dose fraction. For a constant population density, the integral in Eq. (15) can be evaluated exactly using the Gaussian function, Eq. (10).[23] The contribution from the region of partial fatalities, $D_0 < D < D_1$ is generally small. To a good approximation, we need only include the region where $D > D_1$ and $L = 1$. We find

$$N \approx \sigma\pi R_B^2 \ln\frac{2800\,f\,F_c\,KT^{0.5}}{D_1} = 2\times10^4\left(\frac{\sigma}{6000/\mathrm{km}^2}\right)KT^{0.6}\ln\left[5.6\,f\,F_c\,KT^{0.5}\right]. \tag{16}$$

Here we have used Eq. (6) and $D_1 = 500$ rads, and scaled to an urban population density typical to the third world.[24] Assuming $f\,F_c \gtrsim 0.5$, this implies several tens of thousands of casualties from a one kiloton weapon.

OTHER WEAPONS EFFECTS

A number of additional destructive effects will be present, although somewhat less destructive to human life than the radioactive fallout described above.

1. **Seismic waves.** Only a few percent of the total energy in a buried nuclear explosion is transmitted as long-range seismic waves. Nevertheless, even a 1-kiloton explosion will cause considerable structural damage due to seismic motion near the explosion. The most serious damage occurs from waves with frequencies ~5–10 Hz, near the natural resonances with the tall buildings. At these frequencies serious structural damage occurs for accelerations $a \gtrsim 1$ m/s^2 (i.e., 0.1 g), and complete destruction for accelerations $a \gtrsim 10$ m/s^2. Empirical data from NTS gives surface acceleration $a \sim$ (2–10) KT$^{0.7}$ R^{-2} cm/s^2, where R is the radius in kilometers from the source. We thus expect complete destruction of buildings due to seismic waves at distances $R \lesssim 0.5$ KT$^{0.35}$ km, and considerable damage out to a distance $R \lesssim$ 2 KT$^{0.35}$ km.
2. **Ground-motion-induced airblast.** When the seismic shock from a buried explosion reaches the surface, the ground moves rapidly up and down like a piston, creating a sharp air pressure pulse. Unreinforced structures are severely damaged at 2 psi and completely destroyed at 5 psi. Using

Figure 6.81 from Reference 16, the peak overpressure from a 1-kiloton explosion will be 2 psi at distance of

$$R \approx 1\ \mathrm{KT}^{1/3} \exp[-\rho D/39\,\mathrm{m\,KT}^{1/3}]\mathrm{km}, \tag{17}$$

where $\rho \approx 2$ gm/cm^3 is the specific gravity of the ground medium.

Thus we expect severe damage to residential housing, and related injuries from falling material and projectiles, over an area of several KT$^{1/3}$ square kilometers.

SUMMARY AND CONCLUSIONS

Proponents of building a new generation of small nuclear weapons have seldom been specific about situations where nuclear devices would be able to perform a unique mission. Their one clear scenario is using these warheads as a substitute for conventional weapons to attack deeply buried facilities. Based on the analysis here, however, this mission does not appear practical or possible without causing massive radioactive contamination.

A low-yield nuclear EPW would still only be able to destroy facilities relatively close to the surface. Despite the increased coupling of a buried explosion, even a 1-kiloton nuclear weapon cannot destroy a structure protected by more than about 30 m of concrete from the point of detonation. Very large yield ($\gtrsim$100 KT) weapons are still required to destroy facilities buried under the equivalent of 100 m of concrete.

The penetration capability of kinetic energy weapons is limited by the strength of the missile casing, and the ability of the weapon components to withstand the shock associated with ground impact. We have shown that 3-meter long missiles, constructed from the hardest steels, cannot penetrate deeper than about 12 m of reinforced concrete. A nuclear explosion at this depth will simply blow out a large crater and generate radioactive material which rains down on the local population as fallout.

NOTES AND REFERENCES

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analysts consider this document to reflect Bush administration views on the recently released Nuclear Posture Review.

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