A NUCLEAR BOMB WORTH MORE THAN ITS WEIGHT IN GOLD

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Introduction

In the December 2013 issue of *Physics Today* David Kramer tells us—in an article titled *A nuclear bomb worth more than its weight in gold?*—that "some critics of the B-61 life extension program question whether the program is necessary." And, "Representative John Garamendi (D-CA) questioned why the B-83, a newer bomb that officials acknowledge won't need a life extension for at least 10 years, shouldn't replace the B-61". Strangely enough the article omits the principal reason why the administration may think the B-61 is worth more than its weight in gold.

The B-61 Mod 11, as stated by Kramer and others, can be configured to have various yields ranging from under 10 kilotons (kt) to 360 kt. But what is far more important is that the B61 is a gravity bomb, meaning that it is a weapon intended to be dropped from aircraft, and is consequently designed to withstand significant *g*-forces. It can therefore, if given a proper nose cone, be deployed as a nuclear earth-penetrating warhead (EPW). While the B-83 is also a gravity bomb—and has been put forth for a nuclear earth-penetrating role—it has a maximum yield far greater than is ever likely to be necessary and is larger and far heavier than the B-61, which would restrict deployment options.

Before discussing the technical issues surrounding earth-penetrating nuclear weapons, a little relevant history may be helpful. During the latter part of the last century, there were deeply buried targets that could only be attacked with surface bursts using high yield bombs like the B53, which remained service until the mid-1990s. It has a yield of ~9 megatons and is heavy and large enough that B52 bombers could only carry a limited number on a given mission. These missions were such that there was a good possibility that the planes would be unable to return. A strategic EPW delivered by either SLBMs or ICBMs was a very attractive alternative.

In the late 1980s there was an Earth Penetrating Warhead Requirements Study[1] for which I served as technical director. At the conclusion of the study, it fell to me to give the final briefing to the Hard Target Kill Steering Group chaired by the then director of the Offensive and Space Systems section of the Office of the Director of Defense Research and Engineering (DDR&E) of the Under Secretary of Defense.

The briefing was devastating to what was supposed to become a multi-*billion* dollar program. This is the only major, high-visibility program I know of that, after having reached Phase II (Feasibility), was redirected to Phase I (Concept Definition). Hundreds of people scattered across the defense establishment had been involved. The program died shortly after my study report was distributed. How and why this happened is a rather interesting story.

During the course of the study I found that the intelligence was severely skewed; the simplified methodology that the community was working with to model the propagation of shock waves through the earth was flawed—and had no experimental basis or theoretical justification; that the method of calculating the coupling of energy from a nuclear burst to the earth as a function of height of burst was incorrect; that existing weapons were capable of destroying a very large fraction of the target base when realistic numbers were used for depth, hardness, and coupling; and that even if a new weapon was needed, relatively simple and cost effective modifications to an existing weapon would suffice. This was after both Livermore and Los Alamos had designed, developed, and tested large yield weapons, far larger than it turned out was necessary.

At the time, the development and testing of nuclear weapons was normally done after a military requirement had been established in Phase III (Engineering Development) not Phase I. This fact turned out to be a crucial driver. At a 1987 meeting at the Defense Nuclear Agency, a high level member of the Office of the Secretary of Defense told me that he was aware of the fuzzy nature of the intelligence data, and that whether or not the requirement is clear, Phase II of the program must be initiated to justify the money spent by the DOE laboratories. Others also informed me that the Air Staff did not see a clear EPW requirement either, but nonetheless would support a Phase II because SAC (Strategic Air Command, which no longer exists) wanted it. At that same period of time, however, a letter from the Office of the Secretary of Defense specified the need for survivability and excluded solo-based weapons.

The B-61 Mod11 is very much a part of this history because using it as an earth-penetrating weapon deployed on cruise missiles was known then as "the interim solution", an option to be avoided if the strategic EPW program was to move forward. In the end, this option became the only solution needed to fulfill national guidance.[2]

Since the time covered by this précis of late 20th century nuclear EPW history the world has dramatically changed. Nonetheless, I suspect the administration would still like to retain a nuclear earth-penetrating capability though its usefulness could well be questioned. An understanding of the technical issues surrounding these types of weapons may be of use to the physics community who are very likely to play a part in the debate over such weapons.

As discussed above, EPWs were developed to attack deeply buried targets by using the shock wave resulting from the explosion to crush them. In the meantime, there has been much discussion of the possibility of developing *low-yield* EPWs to penetrate into the earth to *one hundred feet or more* to incinerate buried stocks of chemical or biological materials. The purpose of the low nuclear yield would be to minimize or eliminate radioactive fallout while achieving high enough temperatures to guarantee complete incineration.

For example, the July 2001 joint DOD and DOE report to Congress on the defeat of hard and deeply buried targets it is stated that: "Nuclear Weapons have a unique ability to destroy both agent containers and CBW agents. Lethality is optimized if the fireball is proximate to the target. This requires high accuracy; for buried targets, it also may require a penetrating weapon system." The 4 July 2003 issue of Science was quoted as saying, with regard to mini-nucs and EPWs, "If we were able to do this research . . . we would be able to knock out chemical [and] biological threats . . . and not cause any collateral damage."

In addition to an introduction to some of the physics involved with EPW effectiveness, I show below that these claims are without merit.

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The technical portion of this article is organized as follows. We begin with a short discussion of the phenomenology of underground nuclear bursts. This is followed by what might be termed a mini-analysis for low-yield EPWs. It begins with a determination of how far into the earth an EPW must go to optimally couple energy to the ground. Next, given the geology at the impact area of the target, one can determine how deep an EPW is capable of penetrating. For EPWs to be effective against a given target, one must determine what parameters characterize the target, the geology within which it is located, and from this information what yield would be required to destroy the target. And finally, but not least, one needs to know where the underground target is located.

Phenomenology of underground nuclear explosions

The phenomenology associated with a shallow underground nuclear burst of a fairly large yield (335 kt) is shown in Fig. 1. The figure shows the configuration at some 200 ns after the weapon has detonated. At that time the energy partition of the "source" is

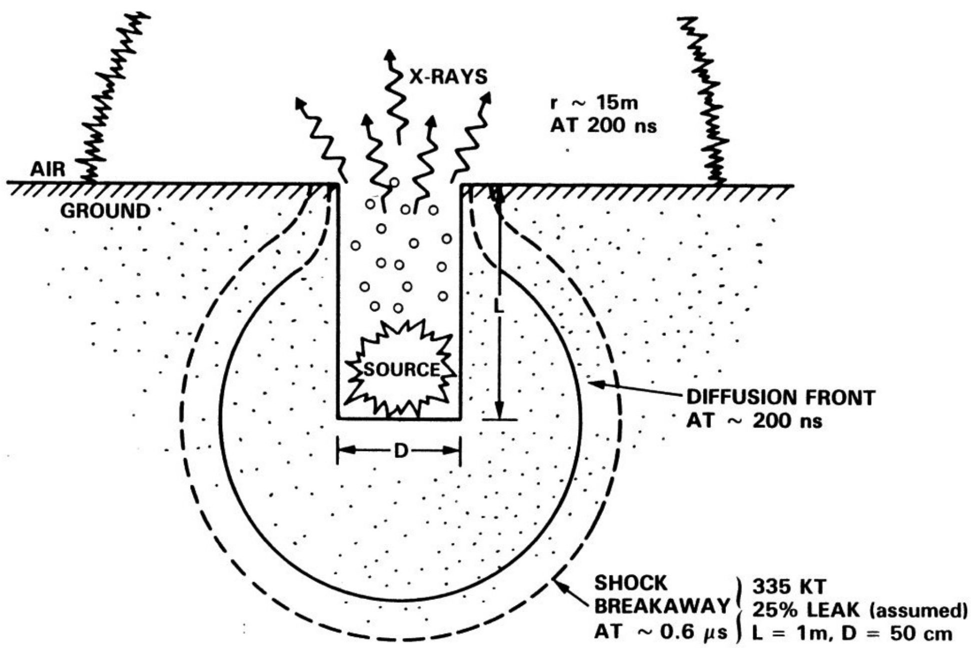


Figure 1. Coupling of the output from a 335 kt nuclear explosion at a shallow Depth of Burst (DOB).

approximately 80% X-rays with a black body spectrum corresponding to ~1-3 keV; 17% debris kinetic energy with a characteristic velocity ~3000 km/sec; and some 2% neutrons having energies of 2 and 14 MeV. The soft X-rays are dominant and are absorbed in a thin layer of earth surrounding the burst thus raising its temperature to an enormously high value. The various forms of energy absorbed produce a very strong shock wave, which subsequently propagates into the ground and also upward where it throws debris into the atmosphere.

Penetration depth needed to optimally couple a low-yield nuclear EPW

Figure 2 gives the equivalent yield-coupling factor (what fraction of energy released by a nuclear weapon is coupled to the ground to produce a shock wave) as a function of scaled depth of burst (DOB). If we ask that the weapon have an equivalent yield coupling factor of ~0.6, the scaled DOB would be around 15 $m/Mt^{1/3}$.

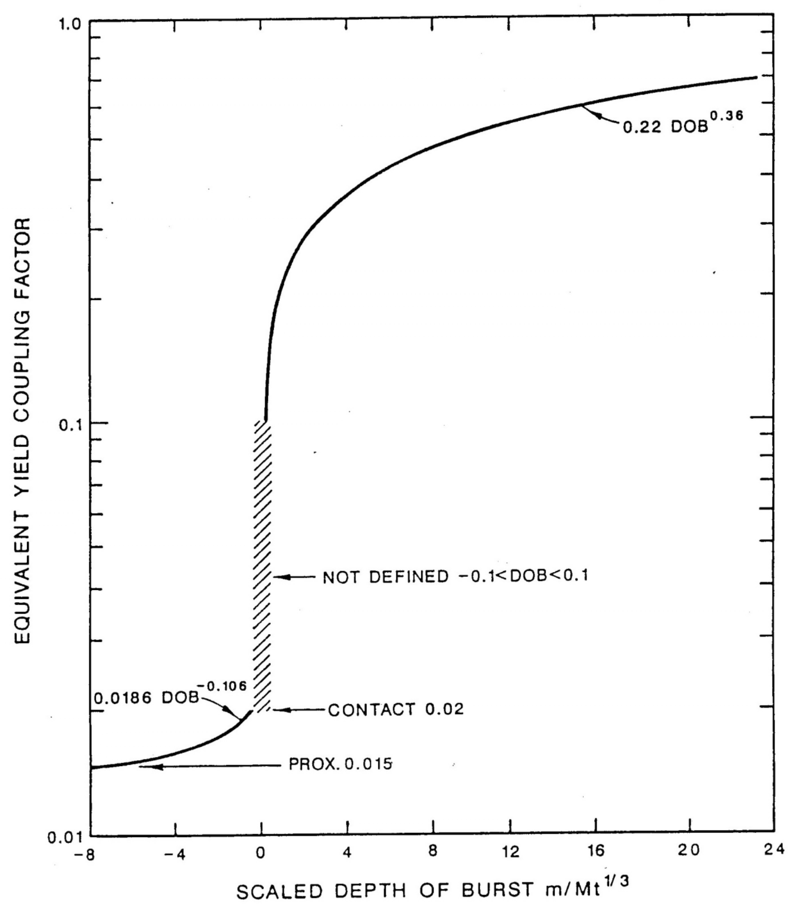


Figure 2. Equivalent Yield-Coupling Factor as a function of Scaled Depth of Burst. A negative scaled depth of burst corresponds to an above ground burst. The equations for the two parts of the curve are given in the figure.

For this coupling factor, a 10 kt burst (10kt = 0.01 Mt) needs to be detonated at a DOB of

$$\text{DOB} = 15\left(\text{m/Mt}^{1/3}\right)\left(0.01\right)^{1/3}\left(\text{Mt}^{1/3}\right) = 15\left(0.216\right)\text{m} = 3.23\text{m}.$$

What this shows is that very good coupling of energy from a nuclear burst can be achieved by detonating the bomb at a relatively shallow depth.

If one is to use an EPW with a small yield nuclear warhead to incinerate buried stocks of chemical or biological weapons, one must determine how deep an earth penetrating warhead can penetrate.• This is answered by the data in Fig. 3.

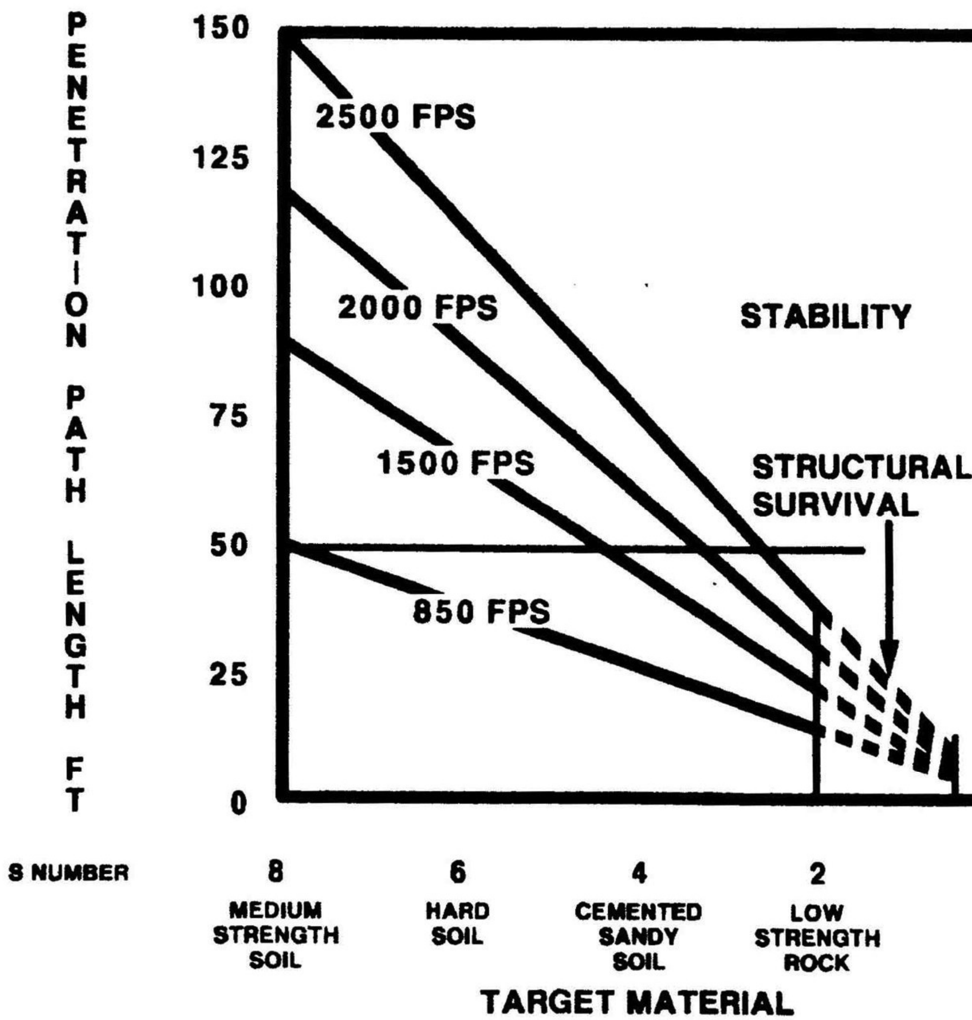


Figure 3. Baseline Strategic EPW Performance. The "Structural Survival" region corresponds to the failure of the EPW. "S" numbers characterize the type of geology.

If we assume that the earth penetrating weapon will be deployed on a cruise missile or is air dropped the relevant curve in Fig. 3, as will be shown later, is the one for 850 feet per second. There is no possibility of reaching depths of 100 feet in any kind of soil, much less rock where one would expect stores of chemical or biological agents or weapons to be stored.

• ICBM or SLBM deployment of EPWs is not considered here. Such deployments require specially designed maneuverable reentry vehicles and a large-scale development program as was considered in the Earth Penetrating Warhead Requirements Study described in the history given earlier in this article.

The general operational limits on EPW designs are an important issue and are better illustrated in Fig. 4.

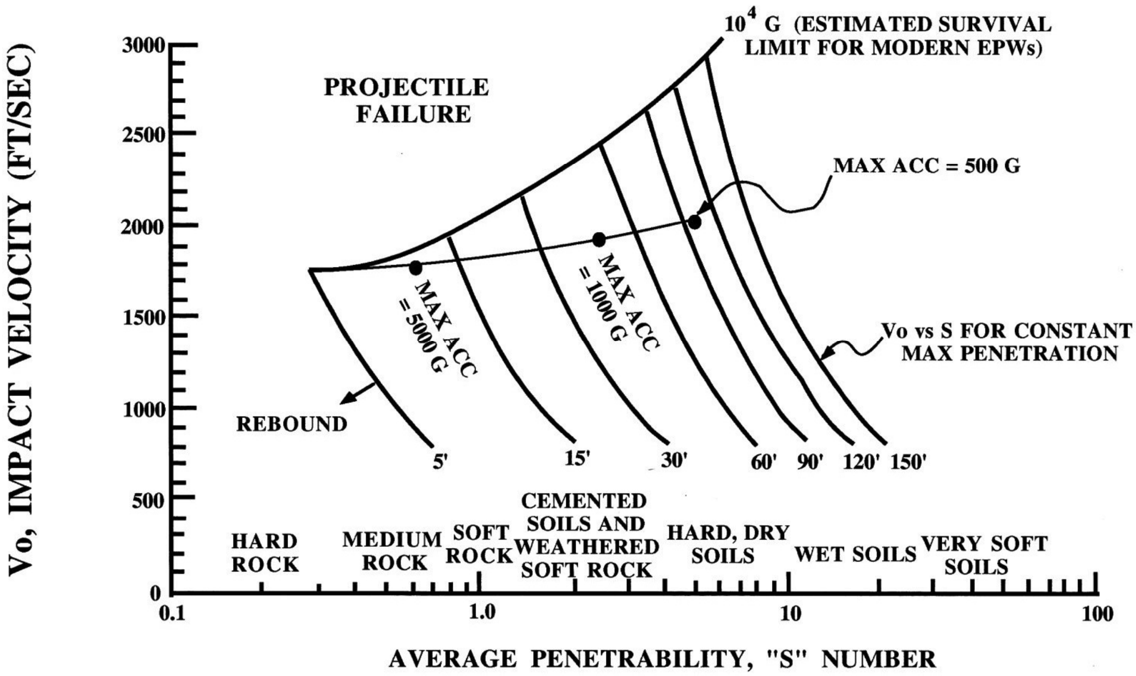
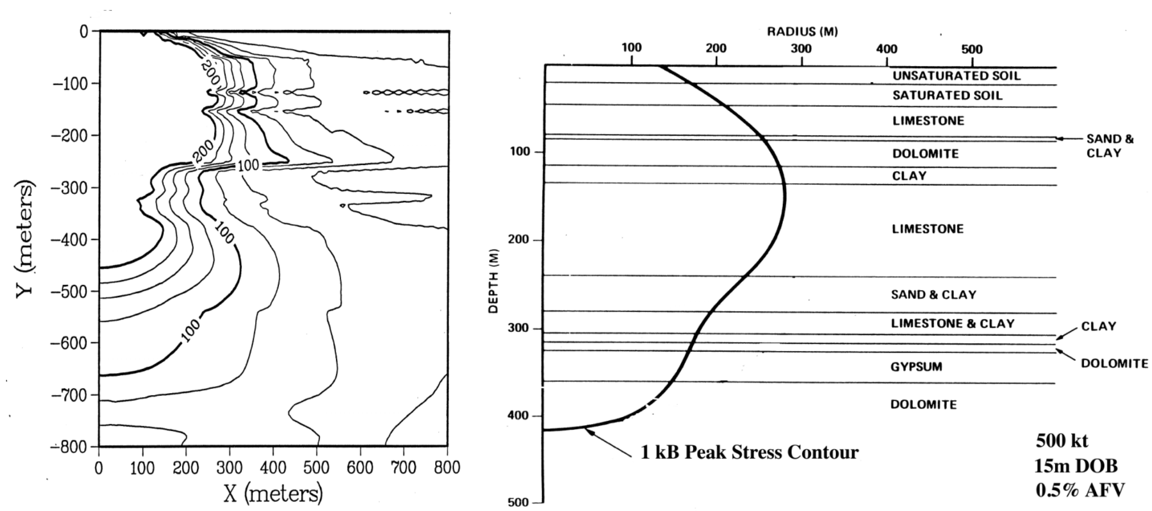


Figure 4. The figure shows the operational limits of current EPW designs imposed by penetrator technology independent of how deployed. This figure does not include limits that may be imposed by other factors such as the nuclear package carried by the EPW.

Required yield

From Fig. 2 one can determine how deep a given yield weapon needs to be buried to achieve a specified coupling of output energy to the ground. How a shock wave resulting from this deposition is propagated through the earth depends strongly on the geology.

Sophisticated modeling is needed to determine peak stress contours as a function of depth and range. Examples of such calculations are shown in Figs. 5(a) and (b). Note that peak stress contours will depend strongly on the type of geology, the air-filled void fraction and the degree of water saturation. Figure 5(b) shows a single 1 kilobar (kb) contour for a 500 kt explosion with a 15 m DOB in a specific geology having a 0.5% air-filled void (AFV) fraction. The attenuation of the shock wave increases with increasing AFV fraction.



(a) (b)

Figure 5. (a) Peak stress contours vs. range for 225 ms after the detonation. Only curves below 1.2 GPa (1 Pa = 10^{-5} bar) are shown. The contour intervals are 25 MPa. This example is for a DOB of 15 m for a weapon having a yield of several hundred kilotons. (b) A single 1 kb contour for a 500 kt explosion with a 15 m DOB in a specific geology having a ~0.5% air-filled void fraction.

On axis peak stress as a function of depth below the burst can also be determined for a given yield and geology. In Fig. 5, this would correspond to a plot of the stress data along the Y-axis (with X = 0) as a function of depth. Curves for different yields can then be found by use of the scaling relationship

$$\frac{Y_2}{Y_1} = \left(\frac{R_2}{R_1}\right)^3.$$

Here *R* is the range to effect.

To decide what yield is needed to destroy a given target, one must choose a depth for the buried facility that is to be targeted, its hardness, and the geology within which it is located. The usual choice for analysis purposes is layered limestone and a hardness to crush the facility of 1 kbar. It turns out that in wet tuff, the type of geology assumed here, the depth of the 1 kbar peak overpressure scales roughly as 50m/kt$^{1/3}$ for a DOB = 1.9 m/kt$^{1/3}$.

This means that if a bunker is at a depth of say 100 m, the yield required for 1 kbar at that depth is given by

$$100 \text{ m} = 50\left(\text{m/kt}^{1/3}\right) \text{Y}^{1/3}$$

$$\text{Y}^{1/3} = \frac{100}{50}\left(\text{kt}^{1/3}\right) = 2\left(\text{kt}^{1/3}\right) \quad \Rightarrow \quad \text{Y} = 8 \text{ kt}.$$

So 10 kt is in the right ballpark for this type of target. The required DOB would be 1.9 $(\text{m/kt}^{1/3})\bullet(8\text{kt})^{1/3}$ = 3.8m. As we have seen, an EPW in this yield range already exist: Although the 2002 Nuclear Posture Review states that the B61 Mod 11 has only a single yield, there is no obvious reason that this warhead cannot be configured to have various yield options.[3] This is why the B61 is the weapon "worth its weight in gold". And in particular, it is also light enough to be deployed on cruise missiles.

Penetration Depth Needed to Prevent Atmospheric Venting

As mentioned above, there has been some discussion of it being attractive to use low-yield nuclear EPWs to incinerate chemical or biological agents since, it has been claimed, the resulting radioactivity would be contained. The depth of burial used at the Nevada Test Site to prevent venting of radioactive debris from an underground explosion is given approximately by[4]

$$\text{D}(\text{m}) \simeq 122 \left[\text{Y}(\text{kt})\right]^{1/3}.$$

For 10 kt, the yield needed to attack the target of the last section, D = 122 $(10)^{1/3}$ = 263 m. Low yield EPWs will definitely vent since, as was shown above, there is no hope of an EPW being able to penetrate to this depth.

EPW Penetration Depth for the B61 Mod 11

To make use of Figs. 3 or 4, we need an estimate of the EPW impact velocity. Two deployment possibilities come to mind for the B61 Mod 11: cruise missiles and air-dropped from say 10,000 ft.

- Cruise Missile (subsonic) ~500 mph = 733 ft/sec
  (Cruise missiles can do a last minute maneuver to increase this impact velocity)

• Air dropped (ignoring air drag):

$$d = \frac{1}{2} a t^2$$

$$v = at$$

$$d = \frac{1}{2} a \left(\frac{v}{a}\right)^2 = \frac{1}{2} \frac{v^2}{a}$$

$$v = (2ad)^{1/2} = \left(2 \cdot 32 \frac{ft}{sec^2} \cdot 10^4 \, ft\right)^{1/2} = 800 \text{ ft/sec.}$$

So both cases give about the same velocity of impact and put us on the lowest curve of Fig. 3 as claimed earlier.

This tells us that in medium strength soil an EPW with a velocity of impact of 800 ft/sec will penetrate less than 50 ft; in low strength rock, maybe 15 ft. How does this translate into the amount of energy coupled to the earth? The answer comes from Fig. 2. The range of the possible penetration depths of 4.6 m to 15.2 m (15 ft to 50 ft) gives us the following table for both ends of the range:

B61 Mod 11 Yield	**SCALED DOB (m/Mt$^{1/3}$)**		**EQUIVALENT YIELD COUPLING FACTOR**	
	4.6 m	**15.2 m**	**4.6 m**	**15.2 m**
10 kt	21.3	70.4*	0.65	>0.7
360 kt	6.46	21.4	0.4	0.68

* Off scale for Fig. 2. Maximum Scaled DOB on that figure is 24 m/Mt$^{1/3}$ corresponding to an Equivalent Yield Coupling Factor of 0.7. This means that a 10kt burst at a 15.2m BOB will be almost fully coupled.

For example, for the 10 kt yield and a detonation at a depth of 4.6 m, the scaled DOB is 4.6(m)/[0.01(Mt)]$^{1/3}$ = 21.3 (m/Mt$^{1/3}$); from Fig. 2, the scaled depth of burst of 21.3 (m/Mt$^{1/3}$) corresponds to an equivalent yield coupling factor of about 0.65.

While the Equivalent Yield Coupling Factor for the B61 Mod 11 set for a yield of 360 kt is only 0.4 when the weapon can only penetrate to 4.6 m into the earth that is considerably better than the 0.02 for a contact burst (see Figure 2). It is interesting to determine the 1 kb stress for this yield option given the DOB range of 4.6 m to 15.2 m.

The data I have is for a 6 m and 12 m DOB rather than 4.6 m and 15.2 m, but these are close enough to get estimates using the scaling relationship given above. As shown in

Fig.6, for a 6 m DOB of a 500kt weapon the 1kb peak stress on axis is at a depth of 465 m. For a 12 m DOB it is 535 m.

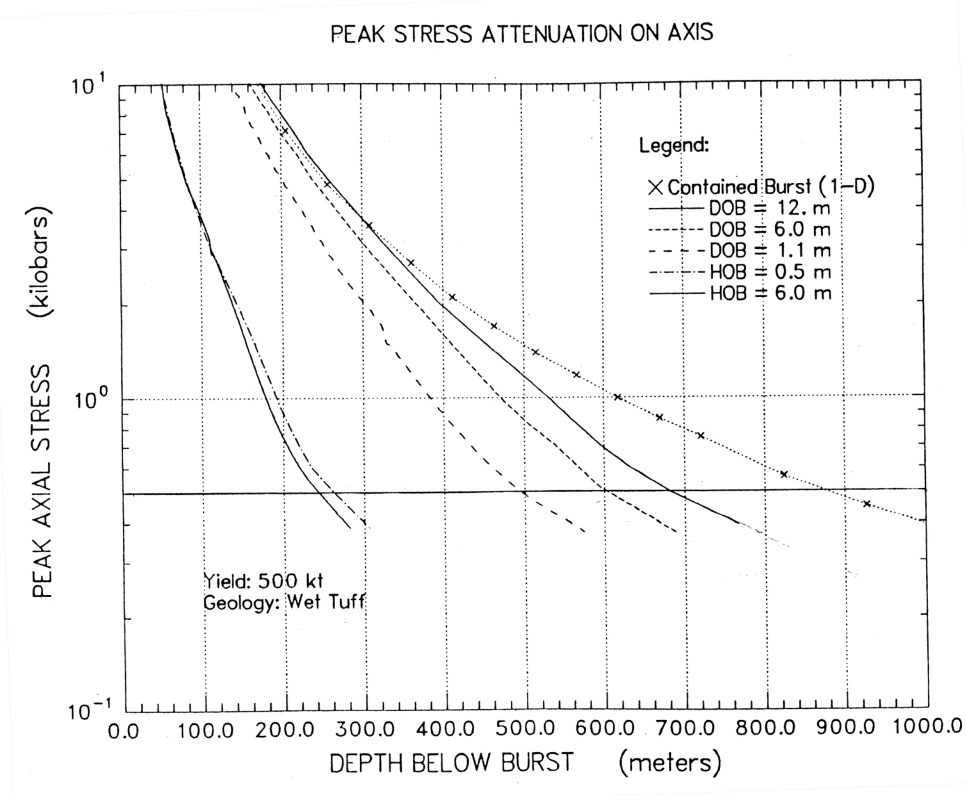


Figure 6. Peal Stress Attenuation on Axis as a function of HOB/DOB.

Rewriting the scaling relationship given earlier in this article, the radius to effect—in this case the depth to 1 kb peak stress—is:

$$R_1 = \left(\frac{360}{500}\right)^{1\backslash 3} 535 \text{ m} = 480 \text{ m.} \quad \left(12 \text{ m DOB}\right)$$

$$R_1 = \left(\frac{360}{500}\right)^{1\backslash 3} 465 \text{ m} = 417 \text{ m.} \quad \left(6 \text{ m DOB}\right).$$

These depths are more than adequate for most potential targets located in geologies where the EPW can penetrate to the depths used in the example above.

Intelligence, rather than technology, is the key issue

Targeting underground facilities requires not only determining their depth and hardness, and in what geology they are located, but also exactly *where* they are located. Intelligence is the key issue. Knowledge of surface-feature locations from satellite or other surveillance photography does not necessarily determine the position or configuration of an underground facility. Without such knowledge (and accurate HUMINT is very scarce in the countries of interest) even relatively large-yield nuclear EPWs may not be very effective. Such weapons also cause severe radioactive fallout due to the venting of activated ground material—unlike bursts at an optimal height chosen to maximize blast damage, which should rule out using many of them over a target area to make up for intelligence deficiencies.

Conclusions

With regard to small-yield EPWs one may conclude:

- To crush a target having a depth of 100m and a hardness of 1 kbar, a low-yield EPW needs a yield of about 10 kt. For this yield, the required EPW penetration depth is around 4m to obtain good ground coupling.
- It is not possible for an EPW to penetrate deep enough into the ground to prevent the venting of radioactive debris or to incinerate deeply buried chemical or biological agents.
- An air dropped or cruise missile deployed EPW cannot penetrate deeper than about 50 feet or 15.2 m in even medium-strength soil, and much less in harder ground.
- The key issue determining the effectiveness of EPWs is accurate intelligence on the location of buried targets, which is rarely available.

Even for far more deeply buried targets, the B61 Mod 11 with a high yield option can produce a 1 kb stress level at depths in the range of 400-500 m. As Figs. 3 and 4 show, however, current technology does not allow EPWs to penetrate hard rock.

REFERENCES

[1] The data and figures in this article are adapted from the contributions of the many people, organizations, and agencies that participated in this study.

[2] The 8 January 2002 Nuclear Posture Review states that: The United States currently has a very limited ground penetration capability with its only earth penetrating nuclear weapon, the B6 Mod 11 gravity bomb. This single-yield, non-precision weapon cannot survive a penetration into many types of terrain in which hardened underground facilities are located" (p. 47). Indeed, penetration of hard rock is a problem; however one wonders how calling this weapon "non-precision" makes sense given the accuracy of cruise missiles. In any case, accuracy is not the principal problem preventing EPWs from being effective.

[3] One of the yields given for the B61 in Chuck Hanson's *Swords of Armageddon* is 10 kt.

[4] J.F. Evernden and G.E. Marsh, "Yields of US and Soviet nuclear tests," *Physics Today* **40**, 36 (1987).