The Nukes We Need:
Preserving the American Deterrent
Technical Appendix[1]

This appendix explains the analysis that underpins arguments in "The Nukes We Need: Preserving the American Deterrent," *Foreign Affairs* (November/December 2009), pp. 39-51.

Questions and comments are welcome. Please direct them to Daryl Press <daryl.press@dartmouth.edu> and Keir Lieber <KAL25@georgetown.edu>.

The Leap in U.S. Nuclear Counterforce: 1985 to the Present.[2]

The leap in U.S. counterforce capabilities over the past twenty-five years can be illustrated by comparing the effectiveness of the most potent counterforce weapon in the U.S. arsenal in 1985 (the Minuteman III ICBM, armed with a W78 warhead) to that in the current force (the Trident II SLBM, armed with a W88 warhead).[3] We model a U.S. strike on an arsenal of twenty missiles deployed in silos hardened to withstand up to 3,000 psi of overpressure. This target set is similar to China's current silo-based ICBM force.

Analysts typically assume that an attack on hardened silos would utilize ground bursts – meaning detonations at or near ground level – because ground bursts maximize the area that is subjected to extremely high levels of overpressure. For ground bursts, the lethal radius (LR) of a given warhead against a given target can be estimated by:

$$(1)\ LR = 2.62 * Y^{(1/3)} / H^{(1/3)}$$

where Y is the warhead's yield in megatons, H is the silo's hardness in psi, and LR is expressed in nautical miles (nm). The odds that a given delivery system (e.g., a missile) will deliver the warhead within the LR, the so-called "single shot probability of kill" or SSPK, is:

$$(2)\ SSPK = 1 - 0.5^{(LR/CEP)^{\wedge}2}$$

where CEP is the delivery system's accuracy.[4]

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[1] We thank Eric Hundman and Austin Grant Long for helpful discussions about conventional counterforce, and Jonathan Chipman for assistance with LandScan.

[2] This section describes the analysis that underpins the arguments on pp. 45-46 about the leap in U.S. counterforce capabilities.

[3] We selected 1985 as the comparison year because Peacekeeper missiles – the first of the current generation of highly-accurate ICBMs – were initially deployed in 1986.

[4] CEP stands for "circular error probable" and is the median miss-distance. In other words, half the warheads land closer to the target than the CEP and half land further away.

The odds of destroying the target must also take into account the reliability (R) of the weapon system. The variable R is a crude estimation of the probability that the delivery system and warhead function correctly. The variable "terminal kill probability" (TKP) incorporates SSPK and R, where:

(3) $TKP = R * SSPK$.

If multiple warheads are sent to destroy a single target, then the target only survives if all the warheads fail. Therefore the odds of destroying the target with n-shots, $p(kill)_n$, is 1 minus the likelihood that every warhead misses, or

(4) $p(kill)_n = 1 - (1- TKP)^n$

When multiple warheads are assigned to destroy a single target, if they are timed to arrive within a short period of time (e.g., to destroy a silo before its missile can be fired), there is a significant danger of fratricide: the possibility that one incoming warhead will interfere with the others. The biggest fratricide risk stems from the problem of the near miss: that a warhead might detonate near the intended target but just outside the LR, creating a dust cloud that shields the target from other incoming warheads. Because reentry vehicles are travelling at great speeds (in excess of Mach 10), even small dust particles might destroy or deflect an incoming reentry vehicle.

It is important to note that when nuclear delivery systems suffer a system failure (e.g., a booster doesn't fire, or a missile's guidance system malfunctions), it does not generally create fratricide risks, because the warheads on the malfunctioning delivery vehicle will not detonate near their targets – if they detonate at all. Therefore, fratricide is only a problem when three conditions are met: (1) the first-arriving warhead and the delivery system carrying it function correctly (i.e., there is no "reliability" failure); (2) the first warhead nevertheless misses the target; *and* (3) the first warhead detonates along the flight path of the other incoming systems. To make a rough estimate of the likelihood of the third condition, we assume that a target is shielded if the first warhead detonates short of the target[5] and without substantial lateral inaccuracy.[6]

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[5] Misses that hit "long" of the target do not generally create fratricide risks for warheads approaching nearby silos because planners are assumed to strike target sets in a back-to-front pattern. It is also worth noting that planners can strike a target with ballistic missiles approaching from multiple trajectories – e.g., with a warhead from an ICBM launched from the continental United States and warheads fired by submarines at different locations. This would further reduce the fratricide problem.

[6] Unless there is bias in the distribution of "near misses," half of the misses will fall short of the target (the other half falling long). We assume that half of those short misses will land close enough to the desired impact point in a lateral direction to put a dust cloud in line with other incoming warheads. We also conducted sensitivity analysis to establish the upper bound for the fratricide problem by assuming that all misses that fall short of the target create a shielding dust cloud. That change increases the fratricide problem, and therefore *increases* the relative advantage of the modern Trident II over the 1985 Minuteman III, because a higher fraction of the Minuteman misses are "near misses," whereas virtually all of the Trident misses are system reliability failures. (Trident II is so accurate that if the weapon system functions, the target is destroyed.)

Unclassified sources suggest that a W78 warhead has a 335-kiloton yield, and a 1985 vintage Minuteman III missile with a Mk-12a reentry vehicle had an accuracy of approximately 180 meters CEP. We assume reliability (R) of 85%. Against a 3,000 psi silo, a single W78 has an SSPK of 69%, and a TKP of 59%. A 4-on-1 attack on a single silo would have roughly a 89% of destroying it; adding two more warheads would only increase the odds slightly, to 90%. Even at 90%, the odds of destroying 20 out of 20 silos are less than 12%.

By contrast, a W88 with a 455-kiloton yield on a 90 meter CEP Trident II missile (R=85%) would have an SSPK of essentially 1.0, and a TKP of 85%. A 4-on-1 attack on a single silo would have in excess of 99% probability of destroying it, and the odds of a 4-on-1 attack destroying all 20 targets would be 97%.

Figure 1 illustrates the probability of destroying a single 3,000 psi silo using various numbers of W78 and W88 warheads (launched by the Minuteman III and Trident II missiles, respectively). **Figure 2** reveals the strategic implications of this leap in counterforce capability by showing the probability of destroying a 20-silo target set. Today, the odds of a disarming strike on a small target set with a multi-warhead attack would depend almost exclusively on target intelligence. If the targets can be found, they can be destroyed.[7]

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[7] Several sources claim that China has deployed decoy silos to complicate an attack on its missile force. There is no evidence at the unclassified level that would allow these claims to be confirmed; nor is there a way to estimate the number of decoys China may have built. However, if these reports are correct, and even if the United States has had no success differentiating decoys from actual silos, the existence of decoy silos would increase the number of warheads required for an attack, but not the likelihood of the attack succeeding – assuming the United States has enough warheads to allocate to real and decoy targets. Attacking large numbers of decoys would, however, increase fatalities in China from an attack. Differentiating real and decoy silos is undoubtedly a high priority for U.S. technical- and human-intelligence.

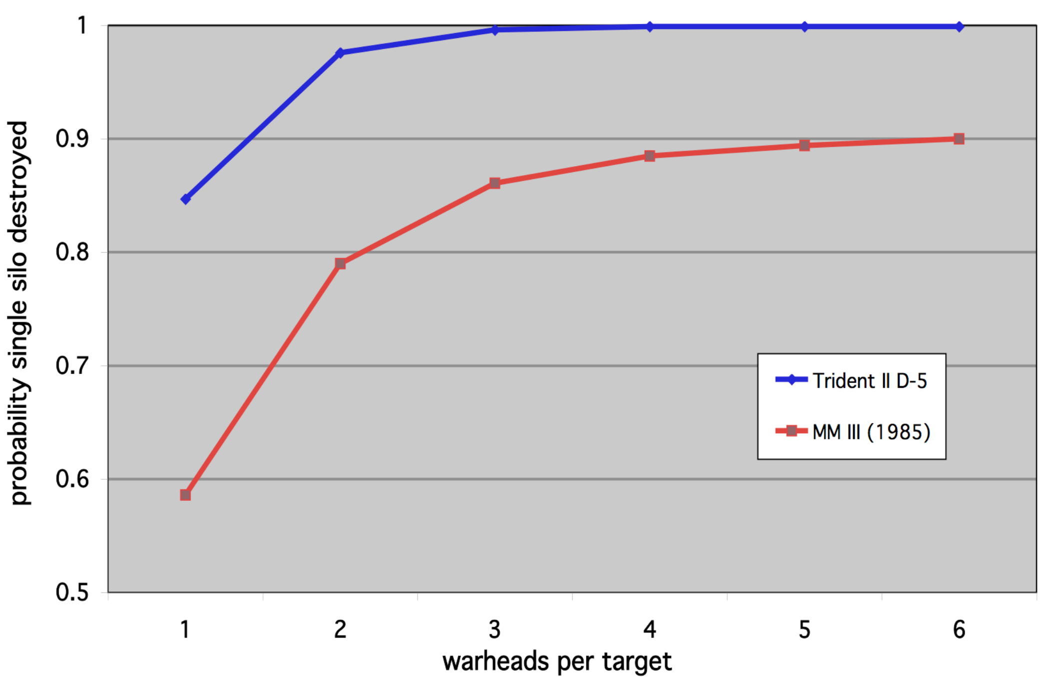

Figure 1: Counterforce capabilities vs. single silo

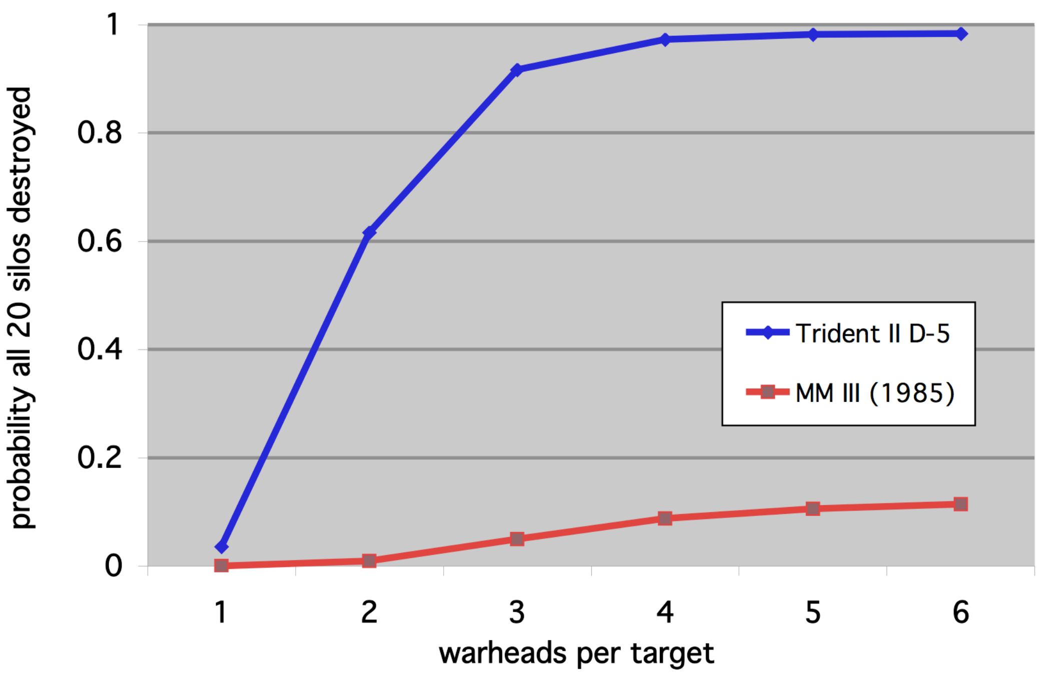

Figure 2: Counterforce capabilities vs. twenty silos

Modeling Fatalities from Nuclear Strikes on 20 ICBMs[8]

We illustrate the potential for low-casualty nuclear counterforce strikes by comparing the expected fatalities from a nuclear strike with high-yield weapons on a small target set to those of a low-yield attack on the same targets. As an example, we target 20 Chinese ICBMs.[9] The precise location of China's silo-based ICBM force is not available at the unclassified level; in fact, whether or not the United States has identified each of China's silos is a very closely guarded secret. A previous study by the Federation of American Scientists and the Natural Resources Defense Council, which modeled a high-yield counterforce strike on China's ICBM silos, hypothetically placed the silo targets in a mountainous region east of Xian, near the city of Luoning, in Henan Province.[10] This is a plausible assumption given the reported basing location of the Second Artillery Corps brigade responsible for the long-range missiles, as well as the strategic value of placing silos in mountainous regions to shield them from some incoming missile trajectories.

In short, we use the same assumed target location as the FAS/NRDC study in order to permit a direct comparison of results: Whereas that study modeled the effect of using high-yield warheads set for ground bursts; we modeled a counterforce strike using low-yield warheads set for airbursts (details below).

Nuclear Effects and Air Bursts

Nuclear detonations cause a series of "prompt" lethal effects (principally from blast and fire) as well as radioactive fallout. Fallout is created after a nuclear detonation occurs near the ground, when debris from the ground is sucked into the hot, ascending air, and mixes with the residual radioactive material from the warhead. As the debris falls back to earth, it spreads lethal radiation.

Targeters have long sought ways to use nuclear weapons to destroy hardened military targets, such as missile silos, without causing massive civilian casualties – for example by detonating the weapons at sufficiently high altitude to prevent fallout – but their efforts have been largely futile. **Figure 3** illustrates the problem. The green line (on the top) indicates the minimum altitude of a detonation to prevent fallout – that is, to prevent ground material from being sucked up into the fireball. The red line (on the bottom) is the maximum altitude of a detonation that can still create 3,000 psi on the ground. The

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[8] This section explains the analysis on pp. 46-47, particularly the casualty estimates.

[9] According to unclassified sources, China has approximately 20 silo-based long-range missiles, plus roughly a dozen mobile ICBMs. Beijing is also working on a submarine-based ballistic missile force, but none of the submarine-based weapons have been deployed. Attacking a small, deployed force of mobile missiles is also possible, but the key factors that would determine success and failure are the quality of real-time intelligence on missile launcher locations, and the time delay between target identification and warhead arrival. Therefore, formulas 1-3 from the previous section are useful for estimating effectiveness against fixed ICBMs, but are not useful for estimating effectiveness against attacks on mobile targets. Estimating the effectiveness of those attacks would require a different conceptual model. If located, mobile missile launchers are far easier to destroy than hardened silos. The analysis later in this appendix that suggests that hardened targets can be destroyed with minimal collateral damage is likely even more true for mobile launchers.

[10] Hans M. Kristensen, Robert S. Norris, and Matthew G. McKinzie, Chinese Nuclear Forces and U.S. Nuclear War Planning (Washington, DC: Federation of American Scientists and Natural Resources Defense Council, November 2006).

problem is clear: for the warhead yields displayed in the figure, there are *no altitudes* that create sufficient destructive effect on the ground without causing fallout – one cannot choose a height of burst that is simultaneously above the green line and below the red one.

But **Figure 4** offers a solution: for very small-yield warheads, there are altitudes that achieve the desired destructive effect on the ground, yet which create virtually no fallout.[11] The problem with using such low-yield warheads, however, is that they require high levels of accuracy.

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[11] The fallout threshold does not create a binary outcome. Above the threshold virtually no fallout occurs, but slightly below the threshold there is little fallout. Figures 3 and 4 are derived from equations in Glasstone and Dolan, The Effects of Nuclear Weapons, U.S. Department of Defense, (Washington, DC: Government Printing Office, 1977).

Fig 3: The Impossibility of High-yield Low-casualty Counterforce

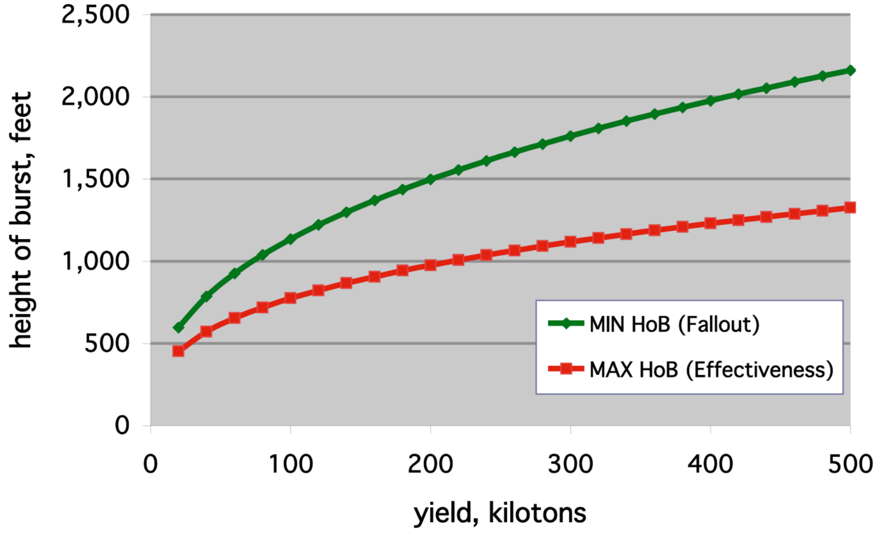
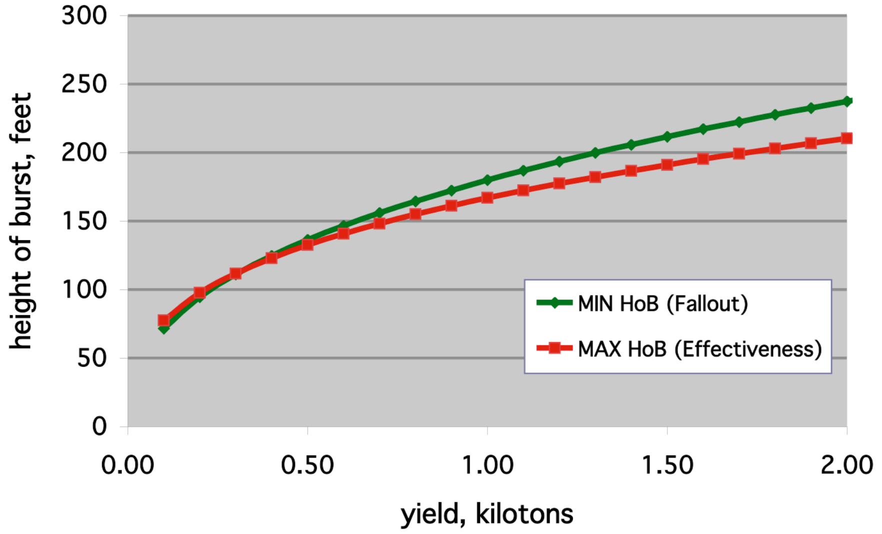


Fig 4: The Low-yield Window for Low Casualty Strikes



Accuracy and Height of Burst

To estimate fatalities resulting from a set of low-yield nuclear strikes we need to specify warhead yields and choose heights of burst (HoBs) for the detonations. For yields, we use 0.3 kilotons, 1.5 kilotons, and 5.0 kilotons, which correspond to open-source descriptions of the lowest yield options on the B61 bomb and the W80 warhead for cruise missiles.

If the goal were to reduce fatalities on the ground, targeters would wish to maximize height of burst.[12] There is a limit to how high they can go: above the red line on **Figures 3 and 4**, the warheads will not produce 3,000 psi on the ground. In fact, as the HoB increases toward the line, the LR on the ground shrinks. How high HoB can be raised, therefore, depends on how accurate the delivery system is (more accurate permits smaller LR), and how many warheads will be assigned to each target (more warheads permits smaller LR, because each warhead can produce a lower TKP and still achieve the desired likelihood of mission success).

We examine the tradeoffs that targeters would face between (a) warhead yield, (b) accuracy, (c) number of warheads per target, and (d) height of burst as the first step to estimate the fatalities on the ground from *operationally realistic* nuclear counterforce strikes. This requires a five-step process.

First, we define the mission goal as: achieve 95% probability of destroying all 20 targets. Second, for each targeting strategy (i.e., 4-on-1, 5-on-1, etc.), we calculate what TKP is required per warhead to achieve a 95% probability of destroying all 20 silos.[13] Third, we calculate what LR is required, as a function of CEP, to achieve the required level of TKP (for a 4-on-1, 5-on-1, or 6-on-1 attack).[14] Fourth, for each warhead yield and targeting strategy, we calculate how high the HoB can be and still produce the required LR.[15] Finally, for those HoBs, we calculate the prompt fatalities as well as the fallout fatalities (calculations described below).

What this method produces is a set of targeting options using different combinations of warhead yields, heights of burst, and warhead numbers. For any level of CEP, this method indicates the number of fatalities that would be produced using any combination of warheads, numbers, and HoBs – holding constant the 95% requirement of destroying all 20 targets. In other words, this method illustrates the range of options available for achieving a 95% "pk-all" against the target set, and the fatalities on the ground associated with each option.

Modeling Prompt Effects of Nuclear Detonations

During the Cold War, analysts used two principal models to estimate the prompt effects of nuclear detonations on nearby civilians: a blast overpressure model and a conflagration

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[12] Increasing HoB reduces fallout. It also slightly increases fatalities from prompt effects. But for these yields and range of HoB, the net effect of increasing HoB generally saves lives.

[13] These calculations can be done by manipulating Formula (4).

[14] This can be done by manipulating Formulas (2) and (3).

[15] We base our estimates on Figures 3.73 in Glasstone and Dolan, Effects of Nuclear Weapons.

model.[16] The overpressure model – which is the standard model – assumes that the percentage of people killed in an area depends primarily on the amount of overpressure to which they're exposed. Intense overpressure crushes structures and turns loose objects into lethal projectiles. Conflagration models are designed to capture the potential consequences of mass fires. For large yield weapons, the thermal effects of nuclear detonations may extend far beyond the range of significant overpressure.[17] Because our analysis focuses on very small yield warheads, the overpressure model is more appropriate for this analysis.

Overpressure models often estimate the relationship between overpressure and fatality rates by extrapolating from the casualty data from Hiroshima. They estimate how much peak overpressure various parts of the city received from the detonation, and compare those "overpressure zones" to the fatality rates on the ground. By doing so, analysts generate a relationship between the overpressure the people in a zone were exposed to and the fatality rate in that zone.[18]

Estimating fatalities using the overpressure model, therefore, only requires four simple steps: (1) estimating the size of each "overpressure zone"; (2) estimating the number of people located in each zone; (3) multiplying the fatality rate by the number of people; and (4) accounting for the cumulative effects of multiple warhead detonations. The size of each overpressure zone can be estimated using Figure 3.73 from the seminal book by Samuel Glasstone and Philip Dolan, The Effects of Nuclear Weapons.[19] Population densities for the mountainous parts around Luoning are available, in 1-km "cells," from LandScan. Approximately 54 people live in every square kilometer in the region in question.[20]

To estimate the consequences of multiple warheads detonating at a single target, we treat each arriving warhead as an independent event. For example, we estimate that a four warhead strike on a given target would kill roughly 95% of the people located in the 5-10

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[16] William Daugherty, Barbara Levi, and Frank von Hippel, "Consequences of 'Limited' Nuclear Attacks on the United States," International Security, Vol. 10, No. 4 (Spring 1986), pp. 3-45.

[17] Theodore Postol, "Possible Fatalities from Superfires following Nuclear Attacks in or Near Urban Areas," Frederic Solomon and Robert Q. Marston, eds., The Medical Implications of Nuclear War (Washington, D.C.: National Academy Press, 1986; see also, Lynn Eden, Whole World on Fire: Organizations, Knowledge, and Nuclear Weapons Devastation (Ithaca, NY: Cornell University Press, 2003).

[18] Daugherty, Levi, and von Hippel, "Consequences," p. 11. In Hiroshima, roughly 95% of the people exposed to 20 psi or more of overpressure were killed. 75% of those exposed to between 10 and 20 psi died. Those exposed to 5-10 psi had a 53% mortality rate, and 12% of those exposed to 2-5 psi died.

[19] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons, 3rd edition, U.S. Department of Defense and Energy Research and Development Administration (Washington, D.C.: U.S. Government Printing Office, 1977), pp. 110-15. The figure shows the relationship between height-of-burst and overpressure for 1-kiloton bombs. The range for any given overpressure can then be scaled for the desired warhead yield; the scaling rules are in Glasstone and Dolan on the same pages indicated above.

[20] We calculated the average population density for two zones which cover the mountains near Luoning. The zones include all twenty hypothesized targets from the FAS/NRDC study, as well as most of the mountainous area around Luoning. According to LandScan data, the average population density is 54 people per square kilometer. We thank Jonathan Chipman at Dartmouth's Applied Spatial Analysis Library for his help with the LandScan analysis.

psi zone, because the odds of surviving each detonation is 47%, and the odds of surviving all four would be 47% to the 4th power. Treating each detonation as an independent event leads us to *significantly overstate* the number of fatalities from the strike, because (a) the people who survived the first detonation are probably those (on average) who are further from the detonation point or in some other favorable protective position, which makes it more likely they would survive subsequent attacks, and because (b) prompt fatalities make up the vast majority of the fatalities in all these strikes. The low casualty estimates we generate may therefore significantly overstate how many Chinese civilians would be killed in such a strike.

For an example, the prompt effects of a 4-on-1 attack on a single silo in the mountains near Luoning, using 0.3 kiloton weapons and 90 feet HoB, would kill virtually everyone within 1,000 feet of the target, and 40% of the people located between 1,000 feet and 1900 feet. Those numbers total 33 expected deaths; attacking 20 similar silos puts the fatalities in the range of 660.[21]

Modeling Fallout.

We use HPAC version 3.2.1 to model fallout fatalities for each combination of warhead yield, number of warheads, and the plausible range of HoBs.[22] For each value of CEP, we seek to identify the targeting strategy that minimizes casualties: we tradeoff HoB vs. number of warheads per target to find the combination that produces the lowest level of fatalities, which we report, as a function of CEP in **Figure 5**.

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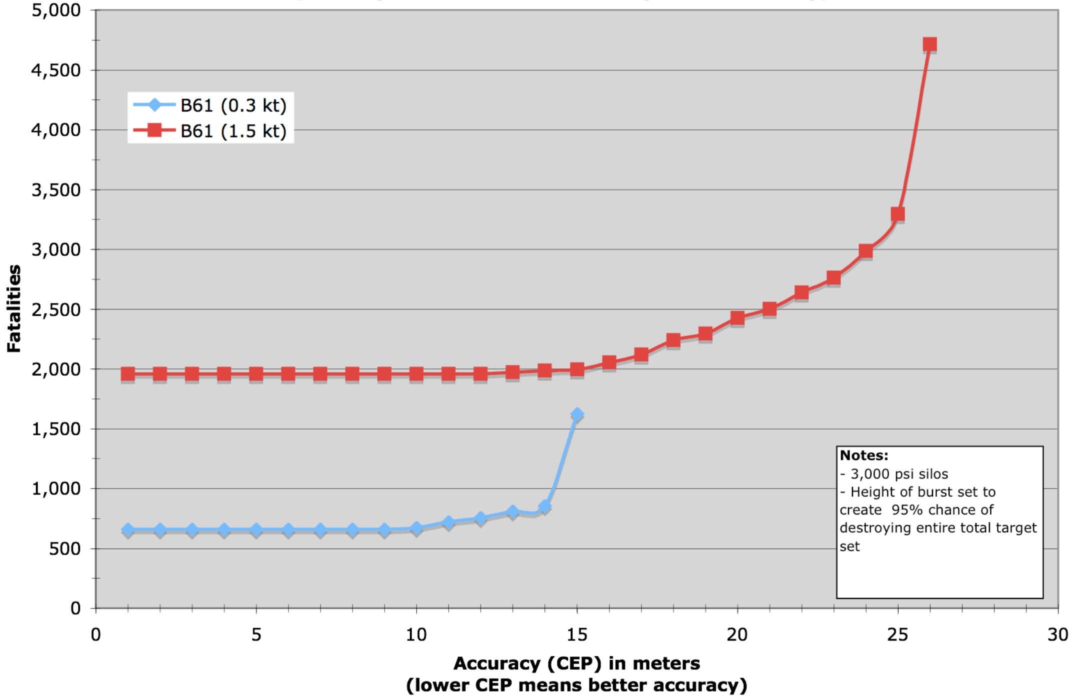
[21] HPAC, the computer program we use to model fallout, also estimates fatalities from prompt effects. Strangely, HPAC – which uses the same LandScan population data that we use – estimates prompt fatalities at roughly 4 times the rate we estimate. This is particularly surprising because we intentionally *overestimate* fatalities on the ground from prompt effects (to make our analysis conservative) by assuming that each warhead has an independent effect on the nearby population (as described above). For the HPAC calculations of prompt fatalities to be correct, the detonations would have to be 100% lethal out to 1 psi – which is implausible. HPAC's problem may stem from the way it calculates population density: it may be using a less fine-grained subset of Luoning, and may have sampled an area outside the mountains, which has 4 times the population density of the mountainous region. Given that all the targets in this analysis are within the mountains, population density calculations should not include the villages and urban areas outside the zone. Note that this apparent problem with HPAC may cause us to overstate the fallout casualty estimates, for which we rely on HPAC – if the software is using questionable data for population density.

[22] HPAC calculates fallout fatalities for two different assumptions – (1) the population remains indoors for 48 hours after the detonations, and (2) the population remains outside. We assume that the population seeks shelter, so we report fatality numbers as a weighted average of indoors (75%) and outside (25%).

Fig 5: Chinese Fatalities from a U.S. Nuclear Counterforce Strike (20 targets in mountainous region of Luoning)



Notes:
- 3,000 psi silos
- Height of burst set to create 95% chance of destroying entire total target set

Comparing Conventional and Low-yield Nuclear Counterforce[23]

We use formulas (2), (3), and (4) to estimate the effectiveness of conventional counterforce strikes against hardened silos. The main obstacle to such an analysis is that formula (1), which calculates lethal radius (LR) of a nuclear warhead of a given yield against a given target hardness, is not appropriate for conventional explosives. The key questions one must address when estimating LR for a conventional bomb against a silo are: (a) will directly striking the silo cap with a bomb destroy or sufficiently damage the silo to make the missile unusable?, and (b) can a bomb of a given explosive power miss the silo cap by any distance and still disable the silo/missile? If so, what is the maximum distance?

There appears to be considerable innovation occurring in the area of penetrators for conventional bombs, aimed to increase their ability to penetrate hard and buried targets. Because some of these innovations may not be reported in the open-source literature, we model a conventional strike in a manner that gives the benefit of the doubt to conventional weapons. This also has the benefit of pushing against the general thrust of our argument, which emphasizes the unique capabilities of low-yield nuclear warheads.

The main 2,000-lb GPS-guided bomb in the U.S. arsenal is the GBU-32, armed with a BLU-109 penetrator. The BLU-109 carries 535 lbs of advanced explosives, which have more explosive power per unit of mass than TNT. One of the first such explosives, Tritonal, is reported to have about 18% increased explosive power relative to TNT. Newer explosives are reported to have up to 50% more.

In estimating LR, the first question is whether a bomb will damage or destroy the silo or missile if it directly strikes the silo cap. One way to assess this is to estimate how much overpressure the bomb creates when it explodes. We use a formula from Gilbert Kinney and Kenneth Graham's book Explosive Shocks in Air[24] to estimate the maximum overpressure created by a GBU-32/BLU-109, as well as the dissipation of overpressure as a function of distance from the detonation.[25] If the bomb carries 535 lbs of advanced explosive, which has the explosive equivalent of between 630 and 800 lbs of TNT (depending on whether one assume 18% or 50% better explosive power than TNT), then the warhead's detonation will create in excess of 11,000 psi of overpressure at the point of detonation (i.e., out to about a tenth of a meter), and will exceed 3,000 psi out to 1 meter (or 1.1 meters if the explosive is 50% more powerful than TNT). A direct hit of the silo cap will, therefore, expose between 3 and 4.5 square meters of silo cap to greater than 3,000 psi and should damage or destroy the silo.

The calculations above also suggest that a bomb might damage the silo if it misses the target by a meter. In fact, this probably underestimates the lethal range of a penetrating

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[23] This section explains the analysis on p. 48 of "The Nukes We Need."

[24] Gilbert F. Kinney and Kenneth J. E. Graham, Explosive Shocks in Air (New York: Springer, 1985)

[25] A BLU-109 has 535 lbs of explosive – or 243 kg. If it is 18% more explosive than TNT, it releases the explosive energy of 287 kg of TNT. Using that figure, we can model overpressure as a function of distance from detonation by using the formulas in Kiney and Graham, Explosive Shocks in Air, 1985, vol. 2. We thank Eric Hundman and Austin Long for helpful discussions about modeling conventional counterforce strikes.

bomb, which is designed to delay detonation until it has penetrated several meters into the concrete or dirt. By delaying detonation until the bomb has penetrated the ground, more of the energy of the explosion is harnessed. To give the conventional bombs the benefit of the doubt, we assume that the bomb can damage the silo if it falls within 1.5 meters of the edge of the silo.

Many large ballistic missiles appear to have silo doors that are slightly more than twice the diameter of the missiles they shield. China's silo-based DF-5 missiles are 3.35 meters in diameter, so we estimate the silo caps being 7 meters across. If the center of the silo cap is the aimpoint, the bomb can miss the target by 3.5 meters and still strike the door. If, for reasons discussed above, the bomb can miss by 1.5 meters and still damage the silo, then LR of the bomb against the silo is roughly 5 meters.

We modeled a conventional strike on the target set of 20 3,000 psi silos using B-2 stealth bombers armed with 2,000-lb GPS-guided bombs. The United States has 20 B-2 bombers. The strike we envision uses roughly a third of the force, or 7-8 aircraft.[26] Each B-2 can carry 16 2,000-lb bombs, so using 7-8 aircraft permits approximately 120 bombs, or 6 per target. GPS-guided bombs can attain an accuracy of about 5 meters (CEP); if GPS is effectively jammed and only inertial guidance is functioning, then we assume that accuracy falls significantly – to 30 meters CEP or greater.[27]

If LR is 5 meters, and CEP is 5 meters, then from Formula (2) SSPK is 50%. Assuming a reliability for U.S. bombs of 90%, TKP = 45% per bomb per silo. A 6-on-1 attack has a 97% chance of destroying each silo, but only (approximately) a 57% chance of destroying all 20. Roughly speaking, there is about a 50% chance of destroying all 20 silos. If GPS is jammed near the targets and CEP falls to 30 meters, the odds of destroying each silo is only 2%, and the odds of destroying them all is virtually zero.

For low-yield nuclear weapons, as we explain in the previous section, we identify combinations of yield, warheads per target, and height of burst to achieve 95% pk-all against the 20 silos. A higher probability of success could be achieved, by lowering HoB, but at the cost of more fatalities.

An important implication of Figure 5 is that while conventional weapons require GPS-like accuracy to achieve good results against hardened silos, low-yield nuclear warheads can achieve 95% pk-all against a 20 silo target set *while minimizing fatalities*, even if the delivery systems cannot achieve pinpoint accuracy. If B-61 bombs were given GPS/INS systems (like those on JDAMs), plus terminal seekers, and GPS was functioning and unjammed during a strike, the bombs could achieve 5 meters CEP and would be expected to inflict fewer than 700 fatalities. If GPS were jammed half way to the target and,

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[26] It is widely reported that B-2s require significant maintenance on a frequent basis to retain their stealthy qualities. Therefore we assume that at most 70% of the force is available for missions at any given time (14 aircraft) and that half of them are tasked with this mission – i.e., 7-8 bombers.

[27] Some analysts report a 30-meter CEP if the bomb's GPS guidance system is jammed, but the bomber can still use GPS. If the bomber and bomb both lose GPS, then accuracy will degrade further. However, as we illustrate below, even 30 meters CEP is too inaccurate for the mission described here.

relying on INS and the terminal seeker, the bombs could “only” achieve 10 meters CEP, fatalities would be in the ballpark of 750. If the United States can develop redundant guidance systems, it should easily be able to achieve less than 15 meters CEP in almost any operational environment – a figure that is low enough to produce small numbers of casualties in strikes like we modeled.