Earth Penetrating Nuclear Warheads against Deep Targets: Concepts, Countermeasures, and Consequences.

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Attacking "hard and deeply buried" targets is the chief justification for developing new capabilities for nuclear weapons or even a new generation of nuclear weapons. The proposed Robust Nuclear Earth Penetrator (RNEP) and possible future nuclear weapons are specifically designed to destroy underground facilities.

This paper very briefly examines the concept of how and why nuclear earth penetrating weapons would be used, a possible countermeasure, and the consequences of their use. We find that attacking underground targets with nuclear weapons is conceptually unsound, countermeasures are available, and the consequences of an attack would be grave.[1]

Concept of Use

When evaluating any new military system, we have to ask: what military problem it is meant to solve, what are the different ways of solving that problem, and how does this proposed system compare to alternative approaches? When applying these questions to nuclear earth penetrators, it quickly becomes apparent that the problem used to justify them is contrived and implausible. The problem is contrived because it is artificially

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[1] This paper extends two previous studies on nuclear attack of underground targets. The first, Robert Nelson, "Low-Yield Earth-Penetrating Nuclear Weapons," *Science & Global Security Vol 10. No. 1, pp 1-20, 2002*, considered low yield weapons, and showed that even small weapons would not be contained and would release substantial amounts of radioactivity. The second, Michael Levi, *Fire in the Hole: Nuclear and Non-Nuclear Options for Counterproliferation*, Working Paper 31 (Washington, DC: Carnegie Institute for International Peace, November 2002), considers large yield nuclear weapons but focues on locating targets, on hard but shallow targets, and on conventional alternatives. This paper tries to complete the survey of the topic—although obviously not all the needed analyses—by focusing on attack of deep targets by large yield nuclear weapons.

constrained to make nuclear earth penetrators appear to be the only solution. The problem is implausible because it assumes a cooperative enemy, it assumes knowledge we cannot have, and it ignores deadly consequences.

Much of the public debate, and many nuclear advocates, confuses earth penetrators with the Administration's discussion of research on "small" nuclear weapons. (Keeping in mind, that on nuclear scales, the definition of "small" is the equivalent of ten million pounds of TNT, or one third the size of the bomb that destroyed Hiroshima, or thousands of times larger than the Oklahoma City bomb.) The proposed nuclear earth penetrators are large nuclear bombs. Small nuclear weapons would not be able to destroy deep targets.

Any suggestion that we need to have more accurate earth-penetrating weapons is also confusing earth penetrators and very small nuclear weapons. A one megaton earth-penetrating bomb will blow out a crater hundreds of meters across. Current guided bombs have accuracies of about one meter. Additional improvements in accuracy are irrelevant to such hugely destructive weapons and weapons any less destructive will not crush deeply buried bunkers. Thus, improvements in currently available accuracy are irrelevant to discussions about the RNEP.

The military threat: neutralizing the physical targets

Over the past twenty years or so, the effectiveness of conventional weapons against hard targets has increased profoundly, a result of on-going improvements in the accuracy of guided bombs and extremely tough steel outer casings allowing them to penetrate meters of concrete without breaking apart. Today, virtually any fixed target on the surface of the earth that can be identified can be attacked and destroyed, as the conventionally armed GBU-28 demonstrated in Iraq. Even shallowly buried concrete structures are vulnerable to conventional weapons. The amount of mass needed to protect against conventional attack is so large that the most economical approach often is not to build ever thicker concrete walls but to dig down into the earth, especially into rock.

Thus, in response to the vulnerability of surface targets, many nations around the world have constructed spaces deep underground to house particularly important

facilities. Now, the United States is confronted with an array of buried targets, perhaps ten thousand,[2] many of which are just beyond the reach of its conventional weapons. Nuclear weapons thus appear particularly attractive—even vital—because, with their greater power, they alone can attack this set of targets.

Neither the Department of Energy nor the Department of Defense has given specific or detailed accounts of how and why nuclear earth-penetrating weapons would be used against deep target. Although lacking specifics, two types of targets are most often discussed. The first is either a storage or manufacturing site for weapons of mass destruction (WMD), either chemical, nuclear, or biological weapons. The second type of target is either political or military leadership, the deep facility providing either a safe hiding place or a protected communications and command center.

A good statement of a military requirement specifies the desired outcome but not how best to accomplish it. The "deep target problem" should be presented as a requirement to neutralize a particular type of threat. Neutralization could be accomplished, for example, by isolating the facility. But an additional constraint that is essential to justify nuclear earth penetrators is that the deep facility must be destroyed, not merely isolated. To know that a deep underground facility even exits, intelligence will have to detect at least one of the entrances. Yet attacking and sealing up the entrances, something that can be done with precision conventional munitions, presumably is not adequate. "Functional defeat," that is, cutting off the electrical power, the cooling, the communication links, and the water, fuel, and air supply is, for some reason, not adequate. It is difficult to imagine a real situation in which this condition obtains, but this assumption is essential if nuclear weapons are to be deemed essential.

One reason presented for target destruction is that the facility might contain dangerous chemical or biological weapons: if a cache of such weapons were attacked with conventional weapons, the chemical or biological agents might be spread around, harming the surrounding civilian population, whereas the heat of a nuclear explosion would supposedly destroy the agents. This scenario does not apply to deeply buried targets because neither the nuclear weapon nor the nuclear fireball penetrate very far into

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[2] U.S. Departments of Defense and Energy, *Report to Congress on the Defeat of Hard and Deeply Buried Targets*, July 2001, p. 8.

rock; a shockwave does and that shockwave might crush the walls of a tunnel but will not produce enough heat to destroy anything. This sort of attack would be effective only against chemical or biological weapons stored on the surface or only shallowly buried.[3]

A potential enemy would not leave valuable, but easily movable, assets in an underground bunker once they become vulnerable. So the logic of requiring destruction—rather than isolation— of the tunnel fails in one of two ways depending on which of two types of notional valuable assets might be contained in a deep tunnel: those assets that are large or permanent are vulnerable to isolation and those that are small and mobile are liable to be moved and not in the tunnel in the first place. A stockpile of chemical weapons or a uranium enrichment plant are examples of the first type. If placed deep enough, even nuclear weapons cannot get to them but the facility is effectively defeated if the entrances and other access to the outside world are attacked and sealed off. A national leader or a single assembled nuclear bomb are examples of the second type of asset. Targets of this type are hard to destroy not because they are deep underground but because they are small and can be hidden in any farmhouse. Saddam escaped destruction not because he was hiding deep underground. He was hiding in houses, which could be easily destroyed, except we did not know which house.

That today's buried targets are just out of reach of today's conventional weapons is not, of course, a coincidence. Digging costs money. Therefore, when deciding how deep to dig, engineers and designers of underground military facilities will estimate the deepest that conventional weapons can reach, dig that deep (plus a safety margin), and stop. Indeed, the United States should *expect* that many buried targets would lie just beyond the capabilities of its conventional weapons. This raises another serious objection to the requirement to destroy rather than isolate deep underground facilities: destruction may very well be impossible. The next section on countermeasures shows that it is quite feasible to continue digging deep enough so that even nuclear weapons cannot reach the deepest tunnels.   In that case, we are forced to revert to the tactic of sealing the entrances and isolating the facility, which conventional weapons can do.

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[3] For attack of near-surface bio-agents see Michael May and Zachary Haldeman, "Effectiveness of Nuclear Weapons against Buried Biological Agents," *Science and Global Security*, Vol. 12 (2004).

The requirements of deterrence

Political realities require that every proposed nuclear weapon or mission be cast in the euphemistic language of "deterrence." No matter that a weapon is carefully tailored for battlefield use, it will always be sold with the disclaimer that it is not for actual use, it is required only to give the appearance of usability, which, in turn, enhances deterrence. (Indeed, the argument is repeatedly offered that by making nuclear weapons more usable, they are better deterrents, thus less likely to be used. Even a simple analysis, however, shows the logic is wrong.[4]) Arguments for nuclear earth penetrators, too, depend on deterrence and its close cousin, dissuasion.

The first step in the deterrence argument is that deterring responsible leaders, that is, leaders who care about the welfare of their people and nation, will be easy because we can threaten to punish their nations by destroying industrial infrastructure, which is very vulnerable. Tyrants like Saddam and Kim, on the other hand, are indifferent to the suffering of their people. They care first about saving their own skin and secondly about maintaining their power. Therefore, we must threaten them directly, personally, or their instruments of power, or something that they specifically hold precious.

Whatever these tyrants most value, they will protect and one way to protect it is by burying it deep underground. To deter tyrants, therefore, we must threaten this valued, buried asset and we can only do that with large nuclear weapons. This requirement is often alternately cast in terms of denying a potential enemy "sanctuary." As Linton Brooks, Director of the National Nuclear Security Agency says, "We fear that a dictator, believing there is nothing we can do to hold at risk the things he values, would be emboldened. And so we think that it is prudent to look at whether or not the President ought to have some tools in his tool kit to hold those things at risk."[5] Note that

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[4] See Ivan Oelrich, Appendix, "Nuclear 'Usability' and the Likelihood of Use," in *Missions for Nuclear Weapons after the Cold War*, FAS Occasional Paper No. 3, January 2005.

[5] Appearing on Public Broadcasting System, *Now with Bill Moyers*, 2 April 2004, [http://www.pbs.org/now/transcript/transcript314_full.html].

There is also concern that an enemy may use sanctuary to hold back weapons that could be used against the United States. "If the United States does not have the means to defeat these facilities [hard and deeply buried targets] and the threatening assets they protect, adversaries may perceive that they have a sanctuary from which to coerce or attack the United States, its allies, or its coalition partners with threats

Ambassador Brooks justifies nuclear weapons because there is nothing we can do to threaten "the things he [the dictator] values," which is obviously not true. There are numerous things that the dictator values that we can destroy. What Brooks's statement can only mean is that we must threaten, not *enough* of what the dictator values, but *everything* he values. There must be no place that is beyond our reach if we want to deter tyrants, so the argument goes. We are meant to believe that, having the entire nation of North Korea to hide in, Kim Jung Il would be more likely to consider starting a war with the United States than if he has the entire nation plus a long tunnel.

To say that sanctuary is unacceptable ignores the whole history of warfare. At no time has any state been able to destroy every asset of its enemies. It is true that, with the huge destructive potential of nuclear weapons in the hands of a hostile regime, it might be reassuring if the United States could destroy every threat facing it. But that does not mean it is necessarily possible. Other approaches are needed, and are possible.

Dissuasion is closely related to deterrence. Some nuclear advocates argue that by making an enemy weapon vulnerable we make it less valuable, therefore a potential enemy is less likely to pursue development of the weapon in the first place. The enemy is dissuaded from a threatening course of action.[6]

North Korea might, for example, be considering developing uranium enrichment facilities capable of producing the material for a nuclear bomb. If these could be destroyed at will by the United States, North Korea might think this course of action is less attractive and not go down that road. But if the facility could be made invulnerable by putting it in a deep underground bunker, then success seems more certain and the North Koreans may be tempted to try it.

This argument requires several wholly implausible assumptions. The North Koreans are now pursuing plutonium production using a reactor and reprocessing facility that are above ground and vulnerable to precision *conventional* weapons. Clearly, fear of US potential is not dissuading them. The United States has not, with one exception, gone

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much more powerful than in past conflicts." From *Report to Congress on the Defeat of Hard and Deeply Buried Targets*, p. 3.
[6] Dissuasion is one of the four goals of nuclear weapons laid out in the *Nuclear Posture Review*, 31 December 2001. From the foreword: "A broader array of capability is needed to dissuade states from undertaking political, military, or technical courses of action that would threaten U.S. and allied security." The unclassified parts of the review are available at
http://www.globalsecurity.org/wmd/library/policy/dod/npr.htm .

to war because a potential enemy is developing threatening weapons. That exception was Iraq. The United States went to war with Iraq because it believed that Iraq was developing nuclear, chemical, and biological weapons. All of the suspected weapon production sites were vulnerable to attack by U.S. precision-guided *conventional* bombs, yet we chose to invade and occupy the country rather than just attack the production facilities. With this history, we want the North Korean leadership to believe that in their case we will use multi-hundred kiloton yield nuclear weapons in a preemptive strike against deep underground production facilities.

Once a bomb is produced and deployed, it is small enough to be hidden anywhere. High-yield earth-penetrating weapons are simply irrelevant to attack on a small, movable target. Production facilities will not prompt nuclear attack and, once a war starts, production will be too slow and too easily disrupted to play a part in the outcome.

How a nuclear earth penetrator would be used

How nuclear weapons destroy underground targets is sometimes not presented clearly and much confusion results.[7] Perhaps inevitably, putting the terms "nuclear earth penetrator" and "deeply buried target" in the same sentence will leave the impression that the nuclear weapon penetrates deep into the earth, down to the target. While deep penetration is possible in soil, no bomb—nuclear or conventional—can penetrate more than several meters in concrete or rock. But these few meters are important; an earth-penetrating nuclear weapon that is even shallowly-buried can produce a shockwave in the ground roughly twenty times stronger than the same weapon exploded on the surface.[8] But it is the shockwave, not the bomb, that penetrates deep into the earth to destroy a buried facility.

A very powerful shock is needed to destroy deep targets. The range of destruction is proportional to the cube root of the force of the explosion. That means, for example, to extend the range by a factor of ten requires increasing the force of the bomb a

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[7] See Jonathan Medalia, *"Bunker Busters": Sources of Confusion in the Robust nuclear Earth Penetrator Debate,* (Washington, DC: Congressional Research Service, 10 January 2005) for an excellent overview of some of the misperceptions in public discussions. In particular, see the illustration from the Philadelphia Inquirer reproduced in Robert Nelson, "Low-Yield Earth Penetrating Nuclear Weapons," *The Public Interest Report*, Vol. 54, No. 1, January 2001, p. 1. [http://www.fas.org/faspir/2001/v54n1/v54n1.pdf]
[8] See Fig 1, p. 4, in Nelson's "Low-Yield," in *Global Security* above.

thousandfold. To destroy deep targets requires very powerful bombs, and current design work on a nuclear earth penetrator is for a bomb with an explosive yield equivalent to a hundreds of thousands of tons of TNT.

The first likely candidate for a rock penetrator is a modification of the Los Alamos weapon, the B-61. It is sometimes cited as having a surface yield of 320 kT, which translates into a well-coupled burial depth of 7 to 15 meters.[9] The other candidate is Livermore's B-83 which is usually assigned a yield of 1.2 megatons so a depth of 10-20 meters will be sufficient.

The bomb would be dropped over the suspected facility. By boring into the rock before exploding, it would create a powerful shock wave intended to crush a tunnel under it. In most cases of interest, the enemy will not dig down, but will dig horizontally into the side of a mountain. So to get "deeper," the tunnel goes further into the mountain to get more of the mountain above it.   The problem then arises that the entrance to the tunnel might be detectable but the tunnel can turn once it is inside the mountain and there is no foreseeable technical way to determine where it is headed. Indeed, it can split up, to create several chambers from one entrance. As the tunnel gets longer and deeper, our ability to determine where the end of the tunnel actually is will go down. Unfortunately, as the tunnel gets deeper, especially as its depth approaches the destructive range of the warhead, the requirement for knowing the exact tunnel location increases. Given uncertainty in the location of the terminus, effective nuclear attack may require barrage tactics, dropping several bombs over the area where the buried facility might be.

Providing the President with options

Finally, there is the question of options. Admittedly, we may not know precisely when, where, and how nuclear earth penetrators might be used, but we want to provide the President with options. (The "tools in his toolkit" in the Brooks quote above.) He almost certainly will not use the weapons, but who would want to *deny* the President a nuclear option? The answer is assumed self-evident.

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[9] This is not to say that penetration to these depths in rock will be possible. Both of the weapons being considered as rock penetrators are two-stage fusion weapons with an implosion primary. What developers are required to do is have the bomb hit the granite with enough force to break it up without damaging the interior of the bomb, for example, cracking the explosive lenses around the primary. It is not clear that this will be possible.

Of course, it is argued, any President should in a time of crisis have as many options as possible. Yet, many times the nation does, indeed, deny the President options. We may "deny" the President the option of violating the laws of physics, because we do not have the ability to provide the option even if we wanted. We have denied the President the option of deploying infantry armed with muskets because the weapons are obsolete and there are better ways of accomplishing their missions. Finally, we deny the President the option of using chemical and biological weapons because we have decided that they are either immoral or, all things considered, their use is not in the best interest of the United States.

Nuclear earth penetrators qualify under all three justifications of denial. Even nuclear earth penetrators cannot eliminate "sanctuary," as much as we may want to, because it is simply impossible. Without perfect intelligence, any farmhouse can be a sanctuary. Nuclear weapons can accomplish some missions but their time has passed for most missions. For example, nuclear weapons could seal the entrances to tunnels, but conventional weapons are almost as effective without the disadvantages. Finally, when we consider nuclear weapons from a global perspective, we see that we have developed a world-wide conventional military advantage and anything that tends to normalize or "conventionalize" nuclear weapons works against our national interests. Thus, the United States may want to deny itself a nuclear option in exchange for a general deemphasis on nuclear weapons and to gain greater international support for non-proliferation.

Motivation for earth-penetrating weapons

Why has the nuclear earth penetrator become so central to the debate about nuclear weapons? Why are we so much more concerned about deeply buried targets now? At the height of the Cold War, nuclear weapons were widely proliferated across a range of weapon systems. The US and the Soviet Union had nuclear-armed air-to-air rockets, nuclear surface-to-air missiles, nuclear depth charges, nuclear torpedoes, nuclear artillery shells, nuclear land mines, and nuclear demolition charges.

One by one each of these nuclear missions was taken over by advanced conventional weapons, not because of arms control agreements or anti-nuclear politics

but because the conventional alternative was militarily superior. Two missions remain for which nuclear weapons are vital: flattening cities and executing a disarming first strike against Russia's strategic nuclear arsenal. Both of these missions are, however, so unsettling that nuclear advocates are not willing to base their requirements on them. The only tactical, "war-fighting" mission left for nuclear weapons that is not patently obsolete is attack of deep tunnels. If this mission follows the nuclear artillery shell and nuclear depth charge into history, there will be no justification for nuclear weapons beyond a small deterrent force. The earth penetrator, the RNEP in particular, is important, even vital, to nuclear advocates because it is the last stand for usable nuclear weapons. But nuclear weapons fall short here as well. Earth penetrators superficially appear useful only under the most artificially contrived circumstances but there is no scenario for their use that actually holds up to examination.

If deep burial were the one remaining technique that an enemy had available to escape the reach of the United States, then nuclear earth penetrators would make more sense. If earth penetrators were the one and only means of protecting the United States from nuclear attack, then their horrendous side effects might be acceptable. But they are not. Nuclear earth penetrators would be, at best, just one part, and not a particularly effective part, of a multi-pronged attack. Thus, the consequences of using, or even planning to use, nuclear earth penetrators must be compared to the benefits and costs of the other methods available to attack a hostile nation's nuclear forces. In the next two sections, we will show that the marginal effectiveness of nuclear earth penetrators—that is, compared to conventional alternatives—is small, potentially zero, while the unwanted consequences are huge.

Countermeasures

If the United States deployed nuclear weapons designed to attack buried targets, one obvious enemy countermeasure is simply to dig deeper. (Other countermeasures are, of course, also available, such as making the targeted assets mobile, dispersed, or camouflaged, but here we only address digging deeper.)   Adversaries could use the same approach to defending against nuclear weapons as they used against conventional weapons: calculate how deep the weapons can reach, dig that far plus a bit more, and

stop. Whether this tactic makes sense depends on the cost and technical difficulty of digging deeper. If current targets, invulnerable to conventional weapons, are at the limit of depths that are easy to reach and going deeper will incur dramatically increased costs, then nuclear weapons will have checkmated the buried facility tactic. If, on the other hand, the cost of digging deeper is manageable down to depths where the facilities would be invulnerable even to nuclear weapons, then the apparent advantage of nuclear weapons is due simply to the fallacy of the last move.

The depth at which a nuclear explosion can destroy a target depends sensitively on the type of target and the type of damage expected or desired. A shallow nuclear explosion—and any nuclear earth-penetrator going into rock would be considered shallow—has three concentric zones of different types of damaging effect, shown in Fig. 1. First, close to the explosion, the material is thrown out to form a crater. Beyond the walls of the crater, the second damage zone will be crushed rock, blending into a layer of fractured rock. (If the explosion occurs in soil rather than rock, there is a zone of compressed soil.) Finally, with increasing distance, the shock wave falls in intensity in the third zone until it becomes an elastic wave, that is, essentially a powerful sound wave, that no longer fractures the rock although these elastic waves can still cause certain kinds of damage.
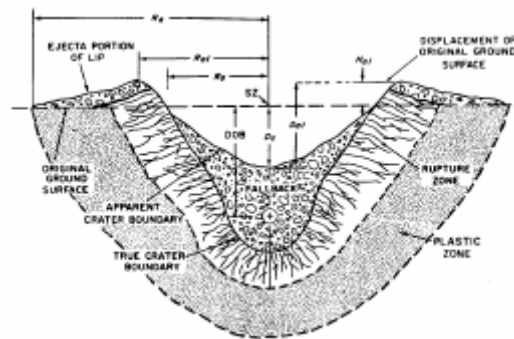

Figure 1. The Anatomy of a Nuclear Explosion Crater
(taken from Glasstone, ref. 24)

Any tunnel that was within the radius of the crater would be destroyed. In fact, the walls of the tunnel would be breached and the hot gasses of the nuclear fireball would

enter the tunnel.[10] Any tunnel in the crushed rock zone would be destroyed and any within the fracture zone could be damaged.

The distances from the point of explosion out to each of the bands of different levels of damage are proportional to the cube root of the yield of the explosion. That means, for example, an eight-fold increase in explosive power doubles the range of destruction and a thousand times increase in explosive power would increase the destructive range by a factor of 10. The range of destruction also depends, of course, on other factors such as the type of rock and whether is it wet or dry. In general, water in the rock increases the shock damage because of the high pressure steam created, the water weakens the rock, and the shock is transmitted better. The nature of the tunnel or underground volume is also important. For example, the strength of a tunnel depends on its size, with smaller tunnels or cavities being more difficult to collapse than larger ones.

Even beyond the range where the rock is fractured, a tunnel could be damaged. The elastic waves are compression waves but with amplitudes that are, by definition, small enough to allow the rock to move and then return to its original position without cracking. One way to visualize this is to picture a small volume of rock that would be pushed out of its normal position by the pressure wave and, once the wave passes, the rock on the far side will tend to push that volume of rock back to its original position. If the pressure wave meets a boundary between rock and air, as it would at the wall of a tunnel, there will not be rock on the other side to push back. Rock is resistant to pressure but typically is approximately an order of magnitude weaker in tension, that is, pulling. Rock along the surface of the wall will be pushed forward by the pressure wave and not pushed back by the air. Elastic forces may not be able to pull the rock in because of its low tensile strength, so the rock along the wall of the tunnel could break free and fly into the volume of the tunnel. This process is called spalling. Even if spalling cannot be relied upon to destroy a tunnel, large amounts of spall could block parts of the tunnel and even small pieces of flying or falling rock could damage equipment in the tunnel or kill personnel.

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[10] Some extremely hard materials have been proposed for missile silos. These might even survive within the lip of the crater. While it is possible that a tunnel lined with such materials might survive inside the crater radius, we do not consider the possibility because, as will be shown later, a cheaper solution is to dig deeper.

Lining the tunnel will prevent spalling. Even without nuclear explosions, mining and tunneling engineers have to worry about rock breaking free from the walls and ceiling of the tunnel. Loose rock can fall out of the tunnel roof and, in deep tunnels, the pressure of the surrounding rock, and sometimes high pressure gas within the rock, can suddenly, even explosively, fling pieces of the wall into the tunnel. These are called rock bursts or popping. Because of the danger of falling rock, tunnels in all but the highest quality, uniform rock are usually lined. Liners may be as simple as wire mesh attached to anchors in the rock. At higher cost, a tunnel might be outfitted with solid concrete liners, which give significant added strength to the walls, or even steel liners that are essentially immune to spall.

Motion alone can cause damage. With spall under control, the tunnel itself is unlikely to be damaged by a passing *elastic* pressure wave. The mass of surrounding rock moves along with the tunnel and the rock and tunnel together move back to their original position once the wave passes.[11] But this rapid movement could damage certain kinds of equipment in the tunnel. For example, at one extreme, high-speed gas centrifuges used to enrich uranium would be particularly sensitive to this sort of motion while they were in operation. At the other extreme, bulk material simply being stored in the tunnel would not be disturbed.

At what point could the tunnel be expected to collapse? The Nevada Test Site is mostly tuff, a compressed aggregate of volcanic ash, so we have limited data on explosions in granite. In one nuclear test in granite, call the Hardhat test, a nearby tunnel carrying testing equipment and cables (see Fig. 2) collapsed at about the point where the peak shockwave pressure equaled the unconfined compression strength of the rock, that is 150 megapascals.[12] If this relationship holds for stronger materials, it suggests an important countermeasure to nuclear attack, namely lining the tunnels with material stronger than the surrounding rock.

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[11] If the tunnel passes through a fault line or between two different masses of rock, then an elastic pressure wave can cause damaging *relative* motion between the two sections of the tunnel with resulting damage along the fault line. This is how earthquakes are most likely to damage tunnels.

[12] Theodore R. Butkovitch, "Calculations of the Shock Wave from an Underground Nuclear Explosion in Granite," *Third Plowshares Symposium: Engineering with Nuclear Explosives*, University of California, Davis, 21-23 April, 1964, pp 11 and 15. [http://www.llnl.gov/tid/lof/documents/pdf/19093.pdf]

The strongest concretes of fifty years ago were not as strong as granite but modern concretes can be stronger. Even greater strength is available at low cost from grey iron, often called cast iron. Cast iron produced in the mid-nineteen century for the Westminster Bridge in London has compressive strength of 40 tons per square inch or 550 megapascals.[13] Today, iron with twice that strength is easy and cheap to produce. The American Society for Testing Materials (ASTM) characterizes cast iron by its tensile (that is, pulling) strength in thousands of pounds per square inch. Thus, an ASTM number of 20 indicates iron that can withstand 20,000 pounds of tension per square inch. Compressive strengths are normally 3 to 4 times tensile strength, so an easily achievable ASTM 40 iron could be expected to have compressive strengths of 140,000 pounds per square inch or 960 megapascals, or about six times stronger than granite.
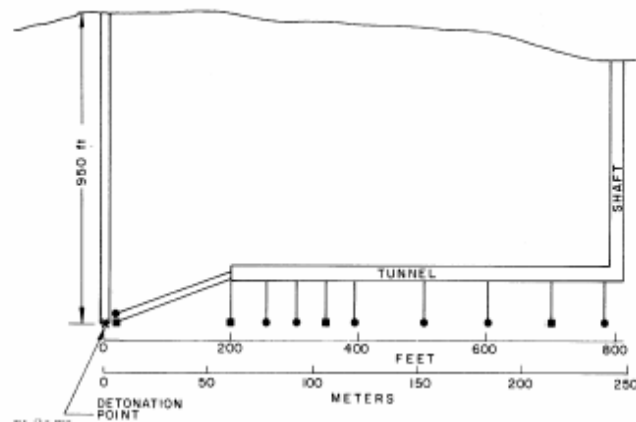

Figure 2. Experimental Arrangement for Hardhat Shot in Granite

(taken from Butkovich, ref. 12)

A notional tunnel four meters across and four meters high could be lined with cast iron supports 15 centimeters (about half a foot) thick for a length of a hundred meters using less than two thousand tons of iron. For comparison, North Korea's largest steel plant, the Kim Ch'aek Iron and Steel Complex, produces six million tons of steel a year.[14] While iron and steel prices vary, and have been higher than average for the last couple of years, grey iron usually costs in the range of $200-300/ton. The lining could consist of

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[13] See "Westminster Bridge Strengthening," http://www.lobeg.com/lobeg/west.html .
[14] See http://www.nti.org/db/profiles/dprk/msl/fac/NKM_F_kimchaGO_bg.html

cast sections of a length equal to the height or width of the tunnel and about a third of a meter wide and would still weight less than two tons each, keeping machine handling simple. The liners would fit within the blasted walls of the tunnel with the space between the liner and tunnel wall being back-filled with high strength concrete.

This current research does not include a detailed finite element analysis to determine exactly how strong such a lined tunnel would be. Based on the correspondence between tunnel collapse and the compressive strength of granite in the Hardhat test, the tunnel might survive at overpressures of 900-1000 megapascals. This would take the tunnel well within the crushed rock zone. We assume that a conservative estimate is that it would survive at least up to the crush/fracture boundary shown in Fig 3, of 200 megapascals.

Is it reasonable to think that only the last hundred meters of the tunnel would be lined? Perhaps not reasonable, but it is consistent. Keep in mind that the justification for deep attack demands that sealing the tunnel entrances is not good enough. Whatever is housed in the tunnel must be destroyed wherever it is.   Certainly there can be no
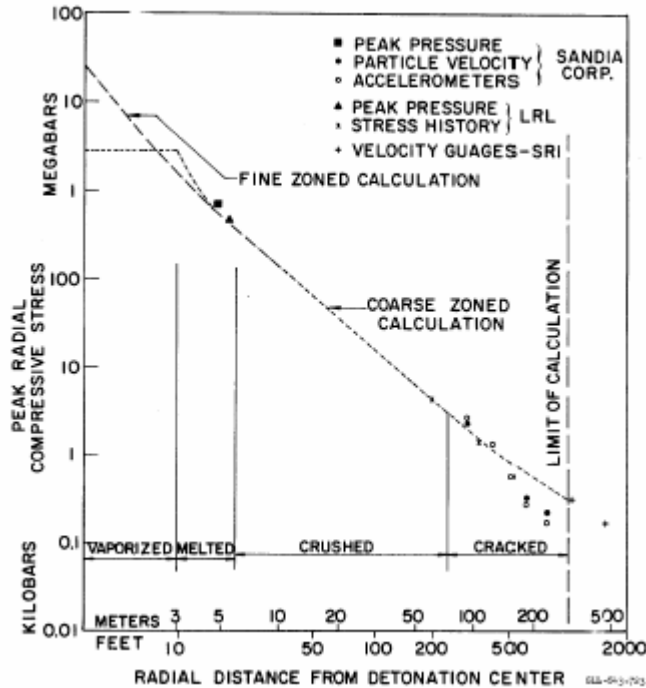

Figure 3. Pressure Distance Graph for the 5 Kiloton Hardhat Shot
(taken from Butkovich, ref 12)

circumstance where sealing up the second hundred meters of the tunnel is adequate but sealing up the first hundred meters, that is, the entrance, is not. This paper argues that this justification for attack of deep targets is, indeed, unreasonable. But that has to be the justification, so lining just the last section of the tunnel may be an unreasonable countermeasure, but it is a consistent countermeasure.

With this hardness, what is the reach of a nuclear weapon? The range of a given shockwave pressure produced by a nuclear explosion scales as the cube root of the yield. That is,

$$R = R_o \cdot W^{1/3}$$

And using the crush ranges of 77 meters for an iron-lined tunnel and 137 for the unlined tunnel for the 5 kT Hardhat shot gives R_o values of 45 and 80 meters. The range as a
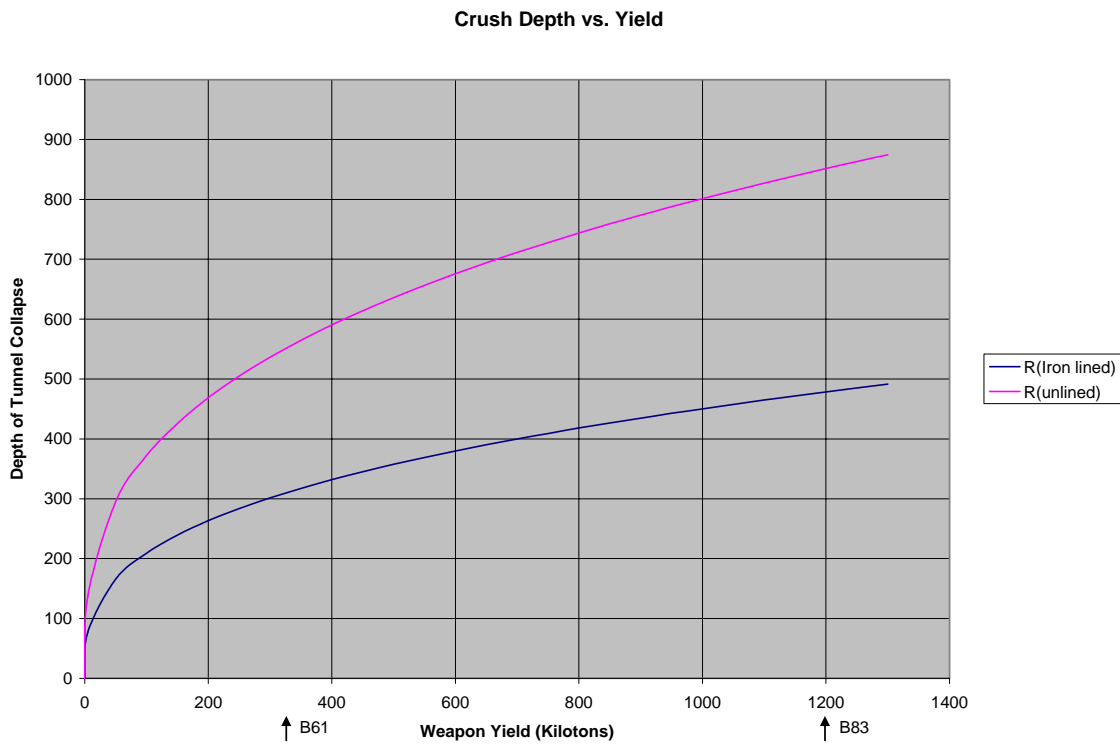
Crush Depth vs. Yield

Figure 4. Crush Depth for Lined and Unlined Tunnels as a Function of Warhead Yield

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function of yield is shown in Fig. 4. (The calculations in the figure neglect the overpressure of the granite itself. We estimate that this understates the weapon range by no more than 10%.)

Note that the B61, with a notional yield of 320 kT, can crush lined tunnels down to 300 meters and unlined tunnels down to 550 meters. Even the B83, with a yield of over a megaton, cannot crush even unlined tunnels under a kilometer of granite.

If the tunnel is going into the side of a mountain that has an average 30 degree incline, a two kilometer horizontal distance translates into one kilometer of depth. Thus, we expect most tunnels of interest here to be at least a couple of kilometers long. We have examined tunnel cost models and empirical cost data and find that over most of the range of interest the costs of tunneling are close to a fixed multiple of tunnel length.

There are two important techniques for tunneling. The older approach, called drill and blast, uses a series of explosions at the tunnel face to blast the rock free. For large tunnels, especially long tunnels, and tunnels built in areas with high labor costs, a tunnel boring machine, or TBM, is more economical. In a tunneling project to bring water to Tijuana, Mexico, projected TBM operating costs were twice the cost of drill and blast per day, but the TBM would have advanced ten times faster, substantially reducing total cost.[15] Nevertheless, for cases of interest to this study, for example Iran or North Korea, we focus on drill and blast costs.

The basic cycle in the drill and blast process is called the "round."[16] The round begins with drilling holes into the tunnel face. Drill bits an inch or more in diameter bore into the rock face one to four meters. Two to four drills are usually mounted on a large movable frame called a "jumbo" and can penetrate a few inches per minute. Depending on the size of the tunnel and the hardness of the rock, a dozen to several dozen holes may be required. Each hole is packed with explosive, usually dynamite or ammonium

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[15] See "Tunnel Investigations and Cost Estimates," Chapter 9 in *The Regional Colorado River Conveyance Feasibility Study, Final Report* (Boyle, 2002). In particular, see Tables 9-16 and 9-17 and compare to progress information on p. 9-8. [http://www.sdcwa.org/news/coloradofeasibility_boylestudy.phtml]

[16] This description is taken primarily from Lyman D. Wilbur, "Rock Tunnels," Chapter 7 in *Tunnel Engineering Handbook*, John O. Bickel and T. R. Kuesel, eds. (Malabar, Florida: Krieger Publishing, 1992), pp 123-207.

nitrate/fuel oil boosted with dynamite. Our notional tunnel four meters across might use 60 kilograms of explosive for a two meter advance per round.[17]

The explosives are detonated in a carefully controlled sequence. Those in the center are blown first to expel a cone of rock from the face, creating a space for the other rock to move into, then along the walls and finally in the corners to create a cleaner cut. The entire firing sequence is only a few seconds.

Once the gases from the explosives have been cleared, the loosened rock, called "muck," is loaded into carts and removed. In some tunnels, the ceiling and walls may need to be secured to prevent rock from falling. At that point, the drilling crew is ready to begin another round.

This description suggest why, when using the drill and blast method, that the great majority of operating costs, both labor and material, are simply proportional to the volume of rock removed. (This also means that a tunnel twice the diameter will require four times the volume of rock removed and will cost approximately four times as much.) That is, a tunnel twice as long will cost approximately twice as much to build.

Some costs are not simply proportional to tunnel length or volume. For example, certain fixed starting costs must be incurred just to secure the external rock face and to start digging. Thus, the first meter into the rock appears more expensive. As planned tunnel length increases, these fixed start-up costs can be amortized over a greater length, reducing the calculated cost per length.

Most additional costs work in the opposite direction, making tunnel costs go up faster than simply proportional to tunnel length. For example, removing the blasted rock is more time consuming as the tunnel gets longer. When the tunnel is a kilometer long, the rock must be hauled a kilometer back through the tunnel for disposal and, obviously, when the tunnel is two kilometers long, the rock must be hauled out two kilometers. Thus, removing the two thousandth meter of rock is somewhat more time consuming and costly than removing the one thousandth meter of rock. That is, the costs go up somewhat faster than merely linearly with tunnel length. According to Norwegian calculations, for our notional 4 meter wide tunnel, cost per length of tunnel is a minimum

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[17] Norwegian Institute of Technology, *Project Report 2A-95, Tunnelling: Blast Design*, University of Trondheim (1995), p 46.

at about 2.5 km. Between three and seven kilometers the cost, per kilometer, increase about 2.5% with each kilometer of additional length for trackless muck carts and only a percent if tracks are laid.[18] (Keeping in mind that laying tracks is more expensive in materials so this is a smaller percentage increase in a larger number.)

The tunnel is, by assumption, working into the side of a mountain. Thus, by design, increased length translates into increased depth and some costs increase as the depth increases. In particular, as the pressure on the surrounding rock increases, greater effort must be made to strengthen the tunnel and secure the rock face. How much effort this strengthening requires depends on the quality of the rock. With weak or fractured rock, the tunnel walls must be secured from the beginning. A tunnel bored into unfractured granite may not require any lining at all even with a kilometer of overburden.

An additional consideration when building deep tunnels is heat. Everywhere on the earth, temperatures increase with depth. In fact, the Swiss use the runoff water from some of their deep tunnels to heat homes near the tunnel entrances. For very deep tunnels, for example deep mines, removing excess heat is challenging. We find that, for tunnels of interest here, some cooling may be required but it will not be technically challenging.[19]

In general, examination of the technical literature shows that tunnels having a kilometer of overburden of hard rock are not considered especially challenging today. Even a kilometer deep, the overburden of granite creates a pressure that is only one sixth or so as great as the unconfined compressive strength of the rock itself. A report from the International Tunnelling Association, specifically examining the special problems of deep tunnels, restricts consideration to tunnels deeper than one kilometer.[20] Several rail tunnels around the world are well over a kilometer deep. The Swiss Loetschberg Base Tunnel has a maximum overburden of 2300 meters. We conclude that if a potential enemy chooses to dig as a countermeasure to potential nuclear attack, the option is technically available. Extending the tunnel beyond the reach of nuclear weapons is quantitatively different, it will take longer, cost more—specifically, the cost will be

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[18] NTNU, Department of Building and Construction Engineering, *Project Report 2C-95, Tunnelling: Costs for Drill and Blast*, University of Trondheim (1995), p 13.

[19] See the appendix for a calculation of the cooling requirements of the notional tunnel.

[20] ITA Working Group No 17 on Long Tunnels at Great Depth, *Long Traffic Tunnels at Great Depth, Executive Summary* (International Tunnelling Association, 2003) [http://www.ita-aites.org/cms/474.html]

closely proportionate to tunnel length—but it is not qualitatively different. Any nation that can dig a tunnel under a hundred meters of granite can dig a tunnel under a thousand meters of granite. Certainly, any nation that can build a nuclear weapon can dig a tunnel under a kilometer of granite.

The degree of control of rock quality is an important difference between tunnels dug in normal engineering projects and the tunnels considered here. A deep or long tunnel typically meets a practical engineering need. Denver needs water and the Colorado River has water but the Rocky Mountains are in between. An aqueduct tunnel through the mountains could connect Denver to this new source of water. The engineer can find the optimal route or declare the whole project infeasible or at least too expensive but cannot change the nature of the rock in the mountain.

The tunnels considered here are quite different. We can find no consideration of using nuclear weapons against potential deep underground tunnels that are being used for *tactical* purposes, such as hiding troops or equipment near the front lines or at key mountain passes. When tunnels are mentioned as difficult, potentially nuclear, targets, their putative purpose is to manufacture or store chemical, biological, or nuclear weapons or to serve as communications or command centers for political or military leadership. These uses allow great flexibility about where to put the tunnel.[21]   Thus, unlike normal civil engineering projects, these engineers *do* have significant choice in rock type. If rock quality is poor in one location, they have the luxury of choosing another.

The harder the rock, the greater the protection if will afford against nuclear attack. But there are some disadvantages to hard rock. A significant fraction of the total costs are the costs of drilling holes for explosive emplacement in the tunnel face. Just the cost of replacing the drill bits can be 7% of the total marginal cost per meter in medium hard rock. Even when using inexpensive explosives such as ammonium nitrate/fuel oil boosted with dynamite, the costs of the explosives can account for 10% of the marginal costs of drilling and harder rock requires more explosive. Finally, drilling harder rock is slower, which also brings higher labor costs.[22]

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[21] *Defeat of Hard and Deeply Buried Targets* cited above does consider tactical targets, and believes they are likely to be hard but not deep. See pp. 8-9.
[22] See *Costs for Drill and Blast*, pp 32-33, 35, and 70.

Hard rock offers some advantages that will tend to lower tunnel costs. Principally, stronger rock allows less elaborate tunnel linings. The simplest solution will be to leave the tunnel unlined, which is most likely to be possible in an unfractured mass of strong rock. But the true cost is not the cost of the tunnel, per se, but the cost of accomplishing the mission. The mission is to protect some asset by tunneling. Even if tunneling in hard rock is more costly, it offers greater protection. The attacking weapon, whether conventional or nuclear, is unable to penetrate far into hard rock and the rock offers greater protection from blast. Thus, the cost for any given level of protection could be lower in strong rock even when the cost per meter of tunnel is higher.

Two of the hardest rocks are granite and basalt. North Korea has both types. Basalt is much more variable than granite but the strongest basalt is stronger than the strongest granite. North Korea has basalt formations in the north along the Chinese border, between longitude 128 and 129 and above latitude 41. This area includes North Korea's highest peak, at 2744 m. While the area is high in general, there are not many peaks to dig under. A more promising area is a large granite formation in the north central region, between longitude 127 and 128 and between latitude 40 and 41. This area, while not as high overall, is much more rugged, offering numerous opportunities to dig horizontal tunnels into mountains with 30 degree slopes to achieve rock depths of a kilometer with only two kilometer tunnels.[23]

It is clear that there are no technical hurdles to digging down deep enough to get beyond the reach of even nuclear weapons. Nuclear weapons, like conventional weapons, can close the entrances to tunnels but neither can crush tunnels at depths that are easy to achieve.

This analysis shows that the apparent attractiveness of nuclear weapons to attack buried targets—specifically those just out of reach of conventional weapons—is simply an example of the fallacy of the last move. We should *expect* to see buried facilities that are just out of reach because that is where potential enemies will naturally stop digging. Faced with nuclear attack, potential enemies could just dig deeper. (As well as other

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[23] Rock types are taken from the *Geological Map of Korea*, 1995, provided by the Korean Institute of Geology, Mining, and Minerals, Daejeon, South Korea. (With thanks to Mr. Sang Chung of the South Korean embassy.) Topology is taken from US Army Corp of Engineers, AMS Series L552, Maps NK52-10 and NK52-8 (1955).

countermeasures not considered here.) There is no qualitative difference, no technical barrier, no skyrocketing cost. Nuclear attack does not solve the problem of deep tunnels. To defeat these targets, we are left with no choice, we have to close up the entrances, attack power, water, air supplies, and cut off communication. That is, we have to achieve a functional defeat. Even if the deepest part of the tunnel is not destroyed, its military effectiveness can be reduced to zero. All of these tasks are better accomplished with conventional weapons.

Consequences.

The previous section demonstrated that nuclear weapons have at best a marginal contribution to US military capabilities, being useful in destroying targets only within a band of depths, that is, greater than can be attacked with conventional weapons but not so deep as to be out of reach even of nuclear weapons.

When making any choice, benefits must be compared to costs. In contrast to the marginal military benefits of nuclear attack of underground facilities, the costs are enormous. The important point that must always be kept in mind is that the proposed earth penetrating nuclear weapons are very high yield. The B61 has a yield estimated to be 320 kilotons, the B83 a yield of 1200 kilotons, or 1.2 Megatons. This is eighteen and sixty times more powerful than the bomb that destroyed Hiroshima. Smaller weapons simply have no hope of crushing even fairly shallow tunnels. The second important point that must be remembered is that the burial of these weapons will be shallow.   For such immensely powerful weapons, the few meters of burial that may be possible will do absolutely nothing to contain the radioactivity.

Using scaling factors found in Glasstone, the B61 would create a crater 200 m (about 700 ft) in diameter.[24] The B83 would create a crater over three hundred meters across, that is a thousand feet, or two tenths of a mile. This is just the size of the *crater*,

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[24] Samuel Glasstone and Philip Dolan, *The Effects of Nuclear Weapons* (Washington, D.C.: United States Department of Defence and Energy Research and Development Administration, 1977), p.235. There may be an inconsistency in *Effect*'s scaling factors. On p. 235 the authors say that the crater created by surface bursts scales as the yield raised to the power of 0.3. Yet on p. 253, the authors say that the crater size of an optimally buried explosion also varies as yield to the power of 0.3. If the buried burst produces this scaling factor only by varying the depth of burst, then it is unlikely the same scaling factor would be produced for a constant, that is zero, depth of burst. We believe that the optimally buried scaling law, which we find in other sources, is correct and the surface burst scaling may have a factor slightly smaller than 0.3.

the area where everything would be obliterated. At far greater distances, the blast and heat would destroy structures and kill people.[25]

Fallout might be even more serious than the blast effects. In the previous section, we considered one region of Korea because of its very rugged terrain but such areas tend not to be heavily populated. The fallout effects will reach hundreds of kilometers from the blast area and can easily reach population centers. Fig. 5 shows the results of a B83 surface burst over North Korea under particular conditions. This is not a prediction. The actual fallout pattern will depend sensitively on wind direction, atmospheric stability, and even whether it rains that day. What the figure shows is a notional, but reasonable, fallout pattern.

The fallout pattern shown in Fig 5 is for the detonation of a 1.2 MT nuclear weapon assuming 50% of the energy comes from fission and an effective wind speed of 30 mph. This wind speed may seem high but this is not the speed of the surface wind but the average wind speed over the whole column of the radioactive dust cloud, which can extend tens of thousands of meters in height. Given the altitudes involved, 30 mph is conservative. The contours are determined from scaling laws found in Glasstone. They show, in a somewhat stylized way, the extent to which the radioactive particles can contaminate the land. After real surface detonations, the fallout of radioactive particles shows more complexity than these simple, clean curves. Real depositions are difficult to predict. An accurate model would require detailed knowledge of the weather patterns during the time of the explosion.[26]

The three contour lines mark the regions where the short-term external doses are 300 rem, 25 rem, and 1 rem. This is the dose one would receive if no precautionary measures are taken from the time of arrival of the radioactive cloud to 4 days (96 hours) after the nuclear explosion. One rem has not been proven harmful; it is equivalent to a CAT scan, or this could be thought of as three to four years (depending on location) of natural background radiation delivered in four days. As a precaution, however, the EPA recommends temporarily evacuating any area where the short term dose is predicted to

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[25] The Federation of American Scientists' website contains a bomb effects calculator, available at http://www.fas.org/main/content.jsp?formAction=297&contentId=367 .

[26] The Federation is developing a much more sophisticated model to predict fallout patterns. Consult the website at www.fas.org.

reach 1 rem or higher as a result of an atmospheric release from a nuclear reactor.[27] A

300 rem dose is thought lethal to 50% of the population. For a dose of 25 rem or higher,

the EPA recommends that emergency workers should enter for lifesaving measures only

on a voluntary basis.[28]

Figure 5. Four-day Exposures for a 1.2 MT Surface Blast and 30 mph Average Winds

We see from the figure that areas of lethal radiation cover significant swaths of

North Korea and radiation levels of concern extend all the way across Japan to Tokyo.

This illustrates the fallout from a single bomb. Remember that before the invasion of

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[27] Environmental Protection Agency, Office of Radiation Programs, *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents*, (Washington, DC) 1991, p. 2-5.
[28] The forthcoming National Academy of Science study on earth penetrating weapons reportedly covers the health effects of nuclear attack in detail.

Iraq, the United States believed there were over a hundred locations associated with WMD production or storage. If multiple sites were hit, each of the weapons would produce a similar amount of fallout with the total effect being cumulative. As discussed in the previous section, lack of knowledge of where a tunnel went once it entered the side of a mountain might require barrage attacks with several nuclear weapons. Again, each detonation would generate a radioactive fallout cloud and the effects would be cumulative. Fig. 5 multiplied a hundred times over would show deadly radioactive contamination covering a large fraction of the total land area of the country. The extensive contamination would make conventional military operations difficult or impossible. Long-term radioactive contamination would thwart the economic recovery of the country. And the cross-border flow of the contamination could permanently damage relations with allies precisely at the time when their support is needed in the conflict.

Conclusions.

This paper has briefly examined (1) the doctrinal concepts for use of nuclear earth penetrators for attack of deeply buried target, (2) one particular countermeasure, digging deeper, and (3) the consequences of such an attack.

Nuclear earth penetrators are the last in a long line of nuclear missions made obsolete by precision guided conventional weapons. Being able to attack buried targets is an important mission. But nuclear advocates have artificially carved out a particular *way* of accomplishing that mission, namely crushing deep tunnels rather than severing their outside connection, not because it is tactically superior but because it seems to make nuclear weapons essential. Nuclear weapons are a hammer and nuclear advocates are trying to manufacture a nail. This report shows, however, that nuclear weapons cannot meet even this mission, tailor made for them. A realistic evaluation of the challenge and the solutions, without presumption that the solution will be nuclear, will steer us in a different direction.

Appendix: Calculation of cooling requirements in a one kilometer deep tunnel in Korea

The average ambient temperature in Chagang Province, the area we are interested in, is 6 degrees C (see http://210.145.168.243/pk/084th_issue/9903303.htm). The temperature gradient in the earth varies from place to place and we do not know what the value is in North Korean granite so we use a high value of 25 degrees C per kilometer. This means that a tunnel one kilometer deep will be 31 degrees C (88 deg F), which is uncomfortable but tolerable for humans and machines. For long-term storage of most materials, and nuclear weapons, no cooling at all would be required. If we wished to keep the tunnel at 20 deg C (68 deg F), it would require cooling.

We used a simple model to estimate the heat loading in the tunnel. Assume a cylindrical horizontal tunnel. Imagine a disk of thickness x_o centered along the centerline of the tunnel. Take a wedge of the disk. The edge of the wedge lies along the centerline and at the wall of the tunnel the wedge intersects a rectangle x_o wide and y_o high. As the wedge extends out into the rock mass, the width will remain constant but the height will grow proportionally to the distance, r, from the centerline.

The heat transfer equation is

$$dQ/dt = k \cdot A \cdot dT/dr \tag{1}$$

that is, the rate of heat, Q, transferred per unit time, t, is equal to the conductivity, k, times the area, A, times the temperature differential along the distance, r, from the centerline of the tunnel.

Note that the area, A, is the cross section of the wedge and a function of r, the distance from the centerline or

$$A_o = x_o \cdot y_o$$

at the tunnel face and

$A = x \cdot y$

Where

$x = x_o$ and $y = y_o \cdot r / r_o$

so that

$A = A_o \cdot r / r_o$

We are assuming steady state condition so dQ/dt is a constant. Since it has the units of power, we rename this constant P,

$P = dQ/dt$

Thus, equation (1) becomes

$P = k \cdot A \cdot r / r_o \cdot dT/dr$

And

$dT = P \cdot r_o / (k \cdot A_o) \cdot dr / r$

Now we need an approximation. If we solve the problem for an infinite wedge, then no heat is conducted into the tunnel in the steady state. (An infinite amount of material with a finite conductivity is a perfect insulator.) Thus, we will say that the wedge reaches the ambient rock temperature in two tunnel radii. This is a conservative assumption, overestimating the heat load. Integrating both sides, we integrate T from the desired

temperature to the ambient rock temperature and integrating r from the rock face to two additional radii, yields

$$\Delta T = P \cdot r / (k \cdot A_o) \cdot [\ln(3r_o) - \ln r_o]$$

To cool the tunnel to 20 deg C requires a ΔT of 11 degrees. The conductivity of different types of granite varies between 2 and 4 watts/K-m so we pick 3. Let the units of r and A be in meters and square meters and use our notional tunnel, which is 4 meters in diameter. With these values, the heat load per square meter is

$$P = 15 \text{ watts/m}^2$$

Our notional tunnel is 4 meters across, the protected space is 100 meters long, yielding an area of 1600 m^2 for a total heat load of 24 kW. Commercial cooling capacity is more often expressed in "tons," that is the cooling equivalent of one ton of ice per day, which is 200 btu/minute or 3517 watts. Thus, our thermal load is just under 7 tons. This value may need to be doubled or tripled to account for heat lost moving the chilled water the length of the tunnel but, even so, this cooling load can be met by a modest commercial chiller. Note that winter temperatures are low and ambient surface air and water can be used to cool the tunnel during the winter months. A thin layer of insulation will significantly reduce the cooling load. Machinery using power, lighting, and people will obviously increase the cooling load.