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DEFEATING HARD AND DEEPLY BURIED TARGETS IN 2035

by

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Biography

Colonel Hart is currently a student at the Air War College, Maxwell Air Force Base, Alabama. Prior to the College, he served as Commander, 31st Test and Evaluation Squadron, Edwards Air Force Base, California, conducting operational test and evaluation of major acquisition programs for Air Combat Command. In staff positions, he has served as the Strategic Communications and Effects Branch Chief, Multinational Security Transition Command-Iraq, the USPACOM Support Team Chief for Information Operations and Strategic Communications at the Joint Information Operations Warfare Command, the Aide-de-Camp/Executive Officer to the Commander, 8th Air Force, and F-16 Flight Dynamics Project Director at Edwards Air Force Base. A Senior Pilot with over 2,000 hours in the B-52, he holds a bachelor's degree in aeronautical engineering from the United States Air Force Academy and a master's in strategic studies from the Naval War College.

Abstract

Underground and hardened facilities are used widely across the globe to protect strategically important assets of nations, to include those related to weapons of mass destruction. Over the last decade, they have presented challenges to the US military for holding such targets of adversaries at risk. Many studies have been accomplished to assess gaps in our military capabilities related to targeting these facilities. Limitations of kinetic weapons to effectively attack these targets highlighted the need to accomplish full-dimensional targeting of underground and hardened facilities in order to defeat them and render them ineffective. The benefits they provide to adversaries in concealment and protection, as well US and partner military limitations to targeting and defeating them, have served to accelerate construction of underground facilities and proliferation of associated technologies among these adversaries.

Improvements in tunneling as well as anti-access/area denial capabilities will serve to compound challenges to targeting underground facilities over the next several decades. As new technologies emerge, specifically related to nanotechnology, hypersonic vehicles, directed energy weapons, and other non-kinetic capabilities, the Air Force must emphasize funding these technologies in order to develop of a family of systems supporting Global Strike forces that will provide the best opportunity for targeting and defeating underground and hardened facilities in the future. Moreover, as the US nuclear stockpile is further reduced and underground facilities are constructed at depths and in materials where current and future kinetic weapons are rendered ineffective, the US military may be unable to hold some of the most critical underground targets at risk. Thus the military may be faced with considering alternative means for holding those targets an adversary deems most vital at risk in order to deter action opposed to US interests.

Introduction

As the Department of Defense considers the changes underway in the emerging strategic landscape of 2035, none are more problematic and of greater strategic concern to US military planners than the explosion in construction of hard and deeply buried facilities around the world. The 2001 Report to Congress on the defeat of hard and deeply buried targets stated that countries such as the former Soviet Union, North Korea, China and former Warsaw Pact countries were prompted to develop a wide range of hardened underground facilities to protect their critical operations and infrastructure from attack during the Cold War. Post-Cold War studies reveal the continued construction of these facilities, to include in Middle Eastern countries, and rogue nations possessing weapons of mass destruction. The intelligence community estimates over 10,000 potential underground facilities exist worldwide, with the majority of them unidentified and the expectation that their numbers will continue to increase dramatically over the next decade.[1]

While the tactic of hardening and burying key facilities to protect them from aerial attack is not new, the availability of improved high-stress concrete materials and dramatically improved tunnel boring technology has made hardened, deeply buried underground facilities among the easier asymmetric countermeasures for adversaries to implement to defeat the US advantage in air-delivered precision guided weapons.[2] Although the US has made significant investments to defeat hard and deeply buried targets since 1999, recent studies show that US military capabilities are becoming much less effective at holding these facilities and other underground facilities at risk. Gaps appear not only in US weapons capabilities to destroy these targets, but also in intelligence capabilities to effectively locate and characterize them.[3]

This paper explores the challenges presented by the hard and deeply buried target (HDBT) problem in 2035 and the capabilities future Global Strike forces require *to defeat* them.[4] It begins proposing a framework with which to evaluate US capabilities against HDBTs. Next, it reviews the progress of recent HDBT defeat efforts and the weapons capabilities these efforts have produced. Third, it explores the gaps that still remain and that are likely to continue into 2035. Finally, it explores technologies and tactics which may narrow these remaining gaps and translates these approaches into required capabilities for Global Strike.

The Department of Defense has recognized the importance of holding HDBTs at risk for some time and has placed considerable resources against the problem for a number of years. There are many technologies that may be leveraged to enhance kinetic, non-kinetic, and directed energy HDBT defeat capabilities and close this gap. However, adversary tunneling, concealment, and anti-access/area denial capabilities, to name a few, are advancing to the point where we may no longer be able to hold the most vital targets at risk. These gaps, moreover, may be compounded by growing economic constraints, future reductions in our nation's nuclear stockpile, and the exponential growth of underground facilities around the globe, making full-dimensional defeat of HDBTs one of our military's greatest challenges in the future.

A Framework to Defeat HDBTs

As a result of capability shortfalls identified after attacks against HDBTs during the 1991 Persian Gulf War, a HDBT Defeat Joint Warfighting Capability Objective (JWCO) was created and validated by the Joint Chiefs of Staff in 1999. The objective of this program, outlined in the *2000 Joint Warfighting Science and Technology Plan* (JWSTP), focused on defeating the military capability held within hardened facilities, rather than physical destruction of the facility alone. The plan's defeat strategy also stressed thinking beyond the immediate target itself,

emphasizing that a full-dimensional defeat approach (Figure 1) consisting of targeting networks, internal vulnerabilities and external vulnerabilities that extend beyond the target's perimeter. For this reason, the plan de-emphasized the term "functional defeat" since it tended to limit thinking "to measures directed at within-facility capabilities."[5] While technology has continued to advance since publication of the plan in 2000, its strategic approach to defeating HDBTs remains pertinent and relevant not only today, but in 2035 as well.

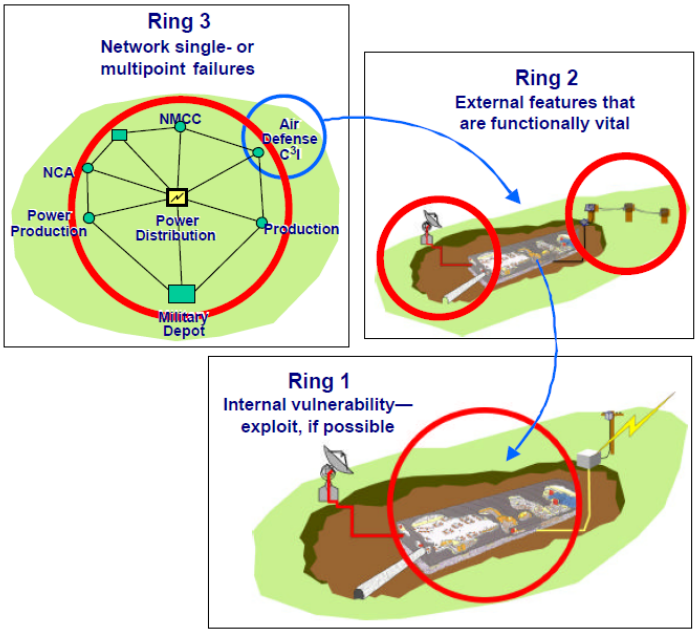

Figure 1. Full-Dimensional Targeting Concept for Hard and Deeply Buried Targets[6]

Current underground facilities are generally comprised of critical utility, communications and air-handling components necessary to perform its mission. These components may reside internally or externally to the facility and may connect to an external network or infrastructure. Such critical components include the following:

- Blast doors, entryway, decontamination room
- Billeting area, bunk beds, pressurized water tank, sewage pump, restrooms, medical station

- Air intake/handlers, NBC filters, blast valves, CO/CO_2 filters, cooling tunnel, sterile air outlet, exhaust fan, fan coil unit
- Food storage, preparation and dining areas, potable water tank
- Diesel water jacket, heat exchanger, water chiller, chiller condenser, local cooler unit, diesel generator
- Communications room, meeting room[7]

In order to exploit vulnerabilities associated with these components and effectively defeat a HDBT, the 2000 JWSTP established the following five core operational capability elements for the full-dimensional targeting process:

- *Detect*—detection of hard and deeply buried targets, and identification of target functionality and network context
- *Characterize*—characterization of hard and deeply buried targets and related network nodes, including geology, structure, information systems, equipment, and status
- *Plan*—target planning
- *Defeat*—neutralization (physical destruction or mission-critical functional disruption)
- *Assess*—combat assessment.[8]

Eighteen functional capabilities support each of these five elements, with several capabilities supporting more than one element. Figure 2 shows how these functional capabilities and elements are related.

Functional Capabilities	Operational Capability Elements				
	Detect	Characterize	Plan	Defeat	Assess
1. Sensors	●	●			●
2. Overcoming Clutter and D&D	●	●			●
3. Sensor Data Fusion	●	●			●
4. Target Database	●	●	●		●
5. C4/Planning and Execution System			●		
6. Connectivity/Integration			●		
7. Delivery Systems				●	
8. Enhanced Weapons for HDBTD				●	
9. Improved Lethality				●	○
10. Survivability	●	●	●	●	●
11. Modeling and Simulation	●	●	●	●	●
12. Simulators and Testbeds	●	●		●	●
13. High-Performance Computing	●	●	○		●
14. Autonomous Systems	●	●		●	●
15. Miniaturized Systems	○	○			○
16. Distributed Systems	○	○			○
17. Preventive Defense	○	○			
18. Decision Process Analysis and Assessment		●	●	●	

● Strong Support ○ Moderate Support

Figure 2. Functional Capabilities Needed for Hard and Deeply Buried Target Defeat[9]

Closer examination of Table 2 reveals that the elements of detect, characterize, and assess are heavily dependent on intelligence collection and sharing capabilities, while the elements of plan and defeat are dependent on targeting information connectivity and integration, delivery systems, and weapons with improved lethality. All elements rely on accurate modeling and simulation capabilities. In order to accurately assess potential HDBTs and capabilities to defeat them, the HDBT Defeat Joint Warfighting Capability Objective considered the following HDBT factors:

- Facility function (command, control, communications and computers intelligence; operations; basing for surface-to-surface missiles, aircraft, artillery, and other systems; production and storage of WMD-related or conventional munitions; and other types of military forces, materiel, and infrastructure)
- Depth of burial or other protective cover
- Physical layout and extent
- Infrastructure features (external and internal)

- Active and passive defenses
- Camouflage, concealment, and deception measures
- Proximity of civilian populations, cultural sites, and other juxtapositions impacting collateral damage assessments
- Susceptibility to hard, functional, and full-dimensional defeat
- Sensitivity to time of delivery[10]

Many of the capability gaps identified by the JWCO in the early 2000s still exist today and may extend well into the future as underground facility numbers multiply and their associated technologies continue to advance. Successfully defeating HDBTs in 2035 requires a family of systems approach to research and development supporting symmetric and asymmetric attack options using conventional and nuclear capabilities. Most important, the relationship of the eighteen functional capabilities to the five functional elements, identified in early research on the problem, will continue to serve as the basis for developing the family of systems for future HDBT defeat efforts.

Current HDBT Defeat Efforts

The *2000 Joint Warfighting Science and Technology Plan* set the path for the development of symmetric and asymmetric functional capabilities to successfully attack enemy underground and hardened facilities. As a result, increased emphasis was placed on new technologies associated with intelligence collection and sharing capabilities as well as kinetic weapon effectiveness. These new technologies have also enabled a more robust, full-dimensional targeting process for defeating HDBTs.

Successful detection and accurate characterization of underground facilities are essential to the HDBT targeting process. As new technologies emerged associated with the various intelligence collection disciplines (geospatial, human, signals, open source, and measurement

and signatures), the Defense Threat Reduction Agency Underground Facility Schoohouse redefined the scope of collection methods for these facilities. The "footprints" of underground facility observable signatures are now categorized as "geospatial" (visible, spectral, and thermal) and "geophysical" (acoustic, seismic, and electromagnetic). These observables can be detected at key external locations or standoff distances. Analytic models using reverse engineering can then be applied to determine the source of the observable signatures. The combination of these signatures creates a footprint that provides clues to the facility's existence, function, and mission.[11] Even as HDBT intelligence capabilities were improved to enhance the operational capability elements of location, characterization, planning and assessment, the Air Force also recognized the need to continue the development of penetrating kinetic weapons to enhance the element of defeat.

Based on lessons learned from striking hardened targets during the first Gulf War and Kosovo, the Air Force continued to emphasize the technological advancement of a family of bombs specifically designed to penetrate HDBTs that require direct over-flight of the target for employment. The current family of weapons includes penetrating bomb bodies attached to conventional guided bomb units (BLU-109, -113, -121B/B, -122, Massive Ordnance Penetrator), as well as earth-penetrating nuclear bombs (B-61 Mod 11).

The BLU-109B is a 2,000-lb class bomb body with 550 pounds of high explosive Tritonal, and is usually mated with a laser guidance kit to form a GBU-24/A penetrator guided bomb. Its advanced-technology, single-piece, high-strength forged steel casing is one inch thick and can penetrate up to six feet of reinforced concrete.[12] It has a delayed-action tail fuze designed to detonate the warhead once it penetrates the hardened facility. These weapons were used extensively during Operations DESERT STORM, ENDURING FREEDOM, and IRAQI

FREEDOM with substantial success. However, intelligence later revealed that some BLU-109s proved ineffective against some of the targets with enhanced hardening measures. Although the weapon may have partially penetrated the hardened surface in these cases, improvements in facility design caused the weapon assembly to either detonate prematurely or fail to detonate.[13]

The 5,000-lb class BLU-113 "Bunker Buster" was designed to hit multi-layered, hardened underground targets during DESERT STORM that were judged to be beyond the BLU-109's capability. During testing, the weapon penetrated well over 100 feet of earth or 20 feet of solid concrete. Designated as a GBU-28 when mated with its guidance package, two BLU-113s were released during the conflict. Sensor imagery of smoke emanating from a port entryway immediately after one of the strikes was the primary source used for battle damage assessment (BDA).[14] This rudimentary method of acquiring BDA information highlighted the challenges associated with post-strike BDA on HDBTs.[15] Recognizing the need to not only penetrate concrete, but rock as well, testing began on an upgraded BLU-113.

In 2003, the Air Force directed the development of the BLU-122, essentially the follow-on from the BLU-113, but with improvements to enable significant penetration through rock. It was designed to "hold 25% more targets at risk, based on a structural or functional kill, as compared to the baseline BLU-113."[16] The weapon incorporates more energetic explosive fill, higher strength case material, modified nose shape for increased penetration, and a joint programmable fuze. However, testing in granite targets revealed problems related to the fuze separating from the main bomb case prior to function.[17] Fuze failures continue to be problematic during counter-HDBT weapon testing due to the inability to accurately model the stresses internal to a bomb body when the bomb penetrates a hard object.

In response to the extreme difficulties of attacking tunneled facilities, a modified BLU-109, the BLU-118/B, was developed. The warhead incorporates an advanced thermobaric explosive designed to generate higher sustained blast pressures in confined spaces, resulting in increased lethality. Concepts for employing the weapon included "vertical delivery with the bomb detonated at or just outside portal, skip bomb with short fuse (first or second contact), skip bomb with long fuse (penetrate door, maximize distance down adits [underground facility entrances or passages]), and vertical delivery to penetrate, overburden and detonate inside the tunnel adit."[18] The weapon was used extensively against Taliban and al Qaeda forces operating out of caves in Afghanistan. The Air Force is now developing the follow-on to the BLU-118/B, the BLU-121B/B, with improved penetration capability and enhanced thermobarics.[19] However, complex entries to tunnel facilities, to include the use of multiple barriers and changing terrain, can render the weapon ineffective.

As countries continue to expand the use of tunneling for underground facilities, testing against facilities protected by rock revealed the ineffectiveness of 2,000 lb penetrating bombs, including use of skip bombing tactics into tunnel entrances. To defeat these facilities, weapons developers determined that several thousand pounds of high explosives "coupled to the tunnel" (i.e., a 20,000-30,000 lb munition) would be required in order to destroy blast doors and send the required overpressure through the complex.[20] Such an optimized penetrator weapon may penetrate 5-8 times farther than current 2,000 lb weapons. In addition, by employing the optimum dual delivery tactic, "where a second penetrator follows immediately behind the first, and boosting the penetrator velocity with a rocket motor, a depth of up to 40 meters can be achieved in moderately hard rock."[21] In response to the 2004 Defense Science Board Summer Study Task Force on Future Strategic Strike Forces, the 30,000 lb Massive Ordinance Penetrator

(MOP) program was initiated. The MOP continues to undergo testing with plans to be employed by the B-2 or Next Generation Bomber. Still, pending the development of accurate and credible intelligence capabilities for tunneled underground facilities, the future success of the MOP remains uncertain.

Although the capabilities of these weapons are impressive, recent studies show that US military capabilities are becoming much less effective at holding HDBTs and underground facilities at risk in many countries. The next section of this paper explains why advancements in tunneling, concrete hardening, camouflage, conceal, and deception measures have created a significant gap in the US military's ability to target underground facilities.

Current and Future Gaps in Defeating HDBTs

Countries across the world increasingly recognize the benefit underground facilities provide in protecting and securing strategic assets. These facilities are becoming "ubiquitous," able to conceal resources, capabilities, and intent.[22] High on the list of nations making significant investments in underground facilities is China, whose underground tunnel network reportedly stretches 5,000 km.[23] China's underground facilities are emblematic of the US HBDT defeat problem, highlighting gaps in intelligence (represented by the operational capability elements of detect, characterize, plan and assess) and weapons capability (represented by the operational capability element of defeat).

Underground facilities are difficult to detect and characterize using traditional US overhead intelligence methods. The list of intelligence and collection gaps against these facilities is long. The inability to accurately identify subsystems internal to an underground facility through imagery is an inherent problem. Advanced camouflage, conceal, and deception capabilities make any subsystems with outlets or components on the surface of the earth virtually

undetectable by current imagery assets. The actual progress in developing robust collection capabilities across all intelligence disciplines has not been as timely and productive as the military has desired. All of this is made worse by advancements in adversary anti-access-related technologies which have only exacerbated gaps related to detection and characterization. Even when the target is found and struck, there is little capability to conduct more than superficial post-strike BDA on underground targets. Sensors do not currently exist that will survive penetration loads and provide real-time information on internal effects and damage to an underground facility.[24]

These intelligence shortfalls aside, the effeteness of kinetic weapons to defeat this class of targets is becoming increasingly problematic. Recent studies have identified revolutionary approaches related to tunnel boring and hardening that make the job of reaching the targets much more difficult with current or near-future kinetic weapons. Such advances have the potential to render current kinetic weapon designs and technology completely ineffective and obsolete. Nevertheless, this widening, hard-kill weapons gap serves reinforce the need for approaches employing *full dimension defeat* of these targets.[25]

Neutralization of an underground facility using full dimension defeat is a formidable task. A 2011 Air Force Scientific Advisory Board study recently reported on its assessment of required approaches and gaps.[26] The emergence of new technologies related to hypersonic travel, nanotechnology and even cyber will play a critical role in these capabilities, but they alone will not provide the "silver bullet."[27] The next section addresses what set of technologies show the most promise to close the gaps in the defeat operational capability element for HDBTs.

Recommendations for Closing the Gap in the Defeat Capability Element

While the future roadmap for targeting hard and deeply buried facilities must emphasize the development of technologies that support all five HDBT operational capability elements (detect, characterize, plan, defeat, and assess), this section focuses on the defeat element. As a result of the 2011 Scientific Advisory Board's findings and the Air Force's 2011 Capabilities Review and Risk Assessment, the Air Armament Center (AAC), in coordination with Air Combat Command, Defense Threat Reduction Agency, Air Force Research Laboratory and USSTRATCOM, is leading development planning for a follow-on HDBT Analysis of Alternatives (AOA) study in 2012. This AOA, led by ACC with support from AAC, will leverage inputs from all communities and organizations researching technologies to enable effective targeting of HDBT in the near and distant (2030) future. As in 1999, future development efforts are focused on developing a "family of systems" to hold HDBTs at risk.[28]

Kinetic Options Against HDBTs

In line with its mission of developing kinetic weapon capabilities, AAC's current HDBT roadmap leverages emerging technologies to produce new kinetic capabilities against HDBT beyond 2030.[29] The ultimate goal of the roadmap is to develop technologies that enable conventional explosive fills with the power of "nuclear" materials, weapons that no longer require a fuze in the explosive train as in today's designs, and weapons with better accuracy than those utilizing the Global Positioning Space system.[30] For the near to mid-term (next 15 years), the roadmap emphasizes the continued development and employment of the BLU-109/113, BLU-121B/B, BLU-122, MOP, and a next-generation, hard-target munition. For the far term (beyond 2031), the roadmap specifies the development of a "high speed penetrator" weapon.[31] The development of such a weapon would occur over three phases, to include an initial High

Velocity Penetrating Weapon, a follow-on Global Strike Penetrating Munition, and the eventual development of an HDBT Functional Defeat Weapon.[32]

The High Velocity Penetrating Weapon (Figure 3) is a 2,000 lb weapon designed to use increased velocity to penetrate HDBTs as effectively as 5,000 lb-class penetrators. It will provide improved penetration capability of HDBTs utilizing high strength concrete (less than 15,000 psi) through boosted impact velocities (2,500 fps) and will operate in a GPS-degraded environment. Its smaller size will enable carriage on the F-35 in order to effectively penetrate enemy anti-access/area denial (A2AD) capabilities and enable increased loadout for other bombers and fighters.[33]

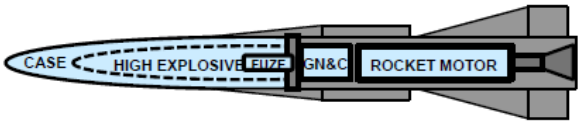

Figure 3. High Velocity Penetrating Weapon Concept

The High Velocity Penetrating Weapon-Conventional Survivable Ordnance Package will be designed with a warhead that will survive and function after boosted impact into a hard target. As the speed of future weapons increases dramatically, terminal guidance and control issues will grow in importance. In addition, new fuze designs will be required to ensure the weapon functions at significantly higher impact velocities than today's gravity-fall weapons.[34]

The Global Strike Penetrating Munition will provide enhanced HDBT penetration (targets hardened to greater than 15,000 psi) through even faster impact velocities (up to 4,000 fps) for targets utilizing high strength and ultra-high performance concrete. Proposals for employing the Global Strike Penetrating Munition include via Sub-Launched Global Strike Missile, an Advanced Hypersonic Weapon, the Biconic/Conventional Strike Missile, or a Long

Range [Hypersonic] Strike Weapon.[35] In addition to enabling a rapid response for time-sensitive hardened targets, the higher speed of these delivery platforms and the warhead itself will promote the survivability of the weapon in A2AD environments. The reliance on the development of hypersonic technologies and capabilities, as well as political influences on the creation of a Sub-Launched Global Strike Missile or Conventional Strike Missile, will play a significant role in the development of this capability. Challenges associated with guidance and control of weapons operating in plasma fields, as well as extreme forces causing large scale deformations in weapon materials, continue to challenge scientists and engineers. In addition, as tunnels and underground facilities are continuously dug deeper in the earth and even stronger concrete is created, kinetic weapons with even greater impact velocities may be required. However, there is a point at which penetration of an HDBT will not be possible, either due to facility depth or level of hardening, or a combination of both.

The far-term Functional Defeat Weapon is a concept driven by the recognition that competition between HDBT technology and kinetic weapon technology may favor the HDBT. Still in the definition stage, this concept requires a coordinated multi-directorate/agency technology demonstrations aimed at finding, characterizing, assessing, and neutralizing HDBTs, while providing innovative techniques to exploit HDBT vulnerabilities. These demonstrations will tackle technological challenges associated with precision effect and placement, sensor data fusion/algorithms/assessment, unconventional fuzing, and novel payloads and materials.[36] These materials may include the use of nanotechnology.

Leveraging Nanotechnology to Enhance Kinetic Weapon Effectiveness

In order to develop an effective family of systems designed to functionally defeat HDBTs, the benefits of nanotechnology cannot be ignored.[37] Recent breakthroughs in

nanotechnology have occurred in a range of relevant specialties from materials to sensors to energetics. The implications of these breakthroughs are that improved ISR capabilities may become available to enhance location and characterization of HDBTs. Moreover, enhanced energetics and improved material properties may improve penetration and thermobaric effects especially against WMD-related materials contained in HDBTs.

Los Alamos National Laboratory (LANL) has made substantial progress in the development of nanotechnology materials designed to enhance weapon penetration/payload survivability and lethality. Scientists have made significant progress in creating core structural properties of materials through the use of nano-sized particles. Much effort has been devoted to

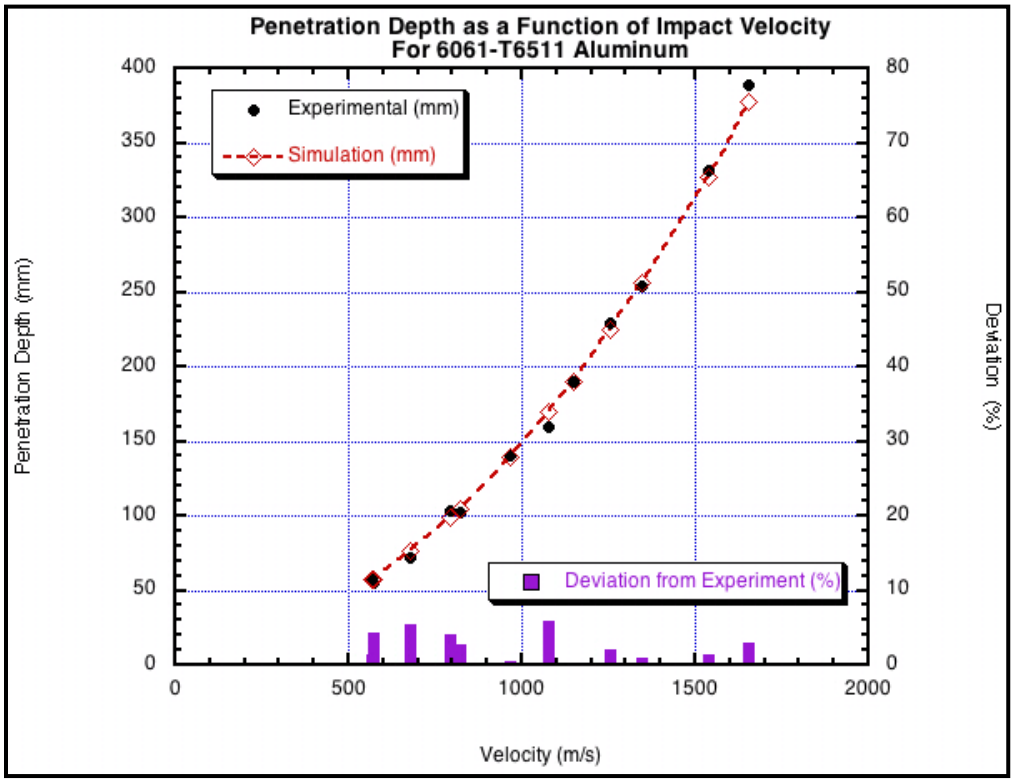

Figure 4. Penetration Depth as a Function of Impact Velocity for 6061-T6511 Aluminum

developing carbon nanotubes, "a naturally self-organized nanostructure (1-2nm width) in the form of a tube comprised of carbon atoms with completed bonds. Carbon nanotubes have 100

times the tensile strength and 5 times the lateral strength of steel, … all at one-quarter the density of steel."[38] Considering the strength of carbon-based nanotechnology, LANL devoted significant effort to modeling penetration mechanics and payload survivability through numerical, empirical, and numerical methods in order to determine the applicability of this technology. As depicted in Figure 4, models show the exponential increase in penetration depth as a function of impact velocity, highlighting the criticality of achieving higher impact velocities while developing materials to withstand the higher velocities.[39] It then researched various materials that would withstand dynamic impacts resulting from hypersonic penetrations.[40] Figure 5 shows the increase in cratering efficiency of materials as their hardness increases.

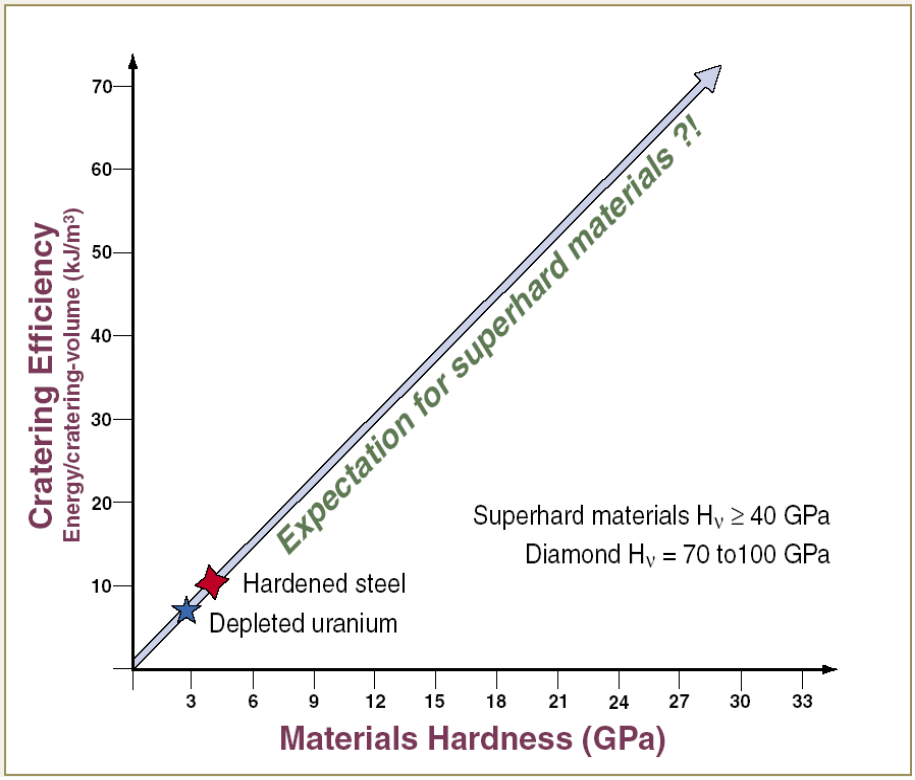

Figure 5. Cratering Efficiency vs. Materials Hardness

Through the development of diamond-SiC nanocomposites, LANL has developed the technology to enhance fracture toughness while maintaining superhardness (Figure 6). Their

efforts revealed that superhard ceramics performed better than metal alloy tips at hypersonic (greater than Mach 5) penetrations.[41] While surviving penetration at hypersonic velocities is critical for successfully striking HDBTs, enhancing the kinetic energy and effects of the weapon is just as vital.

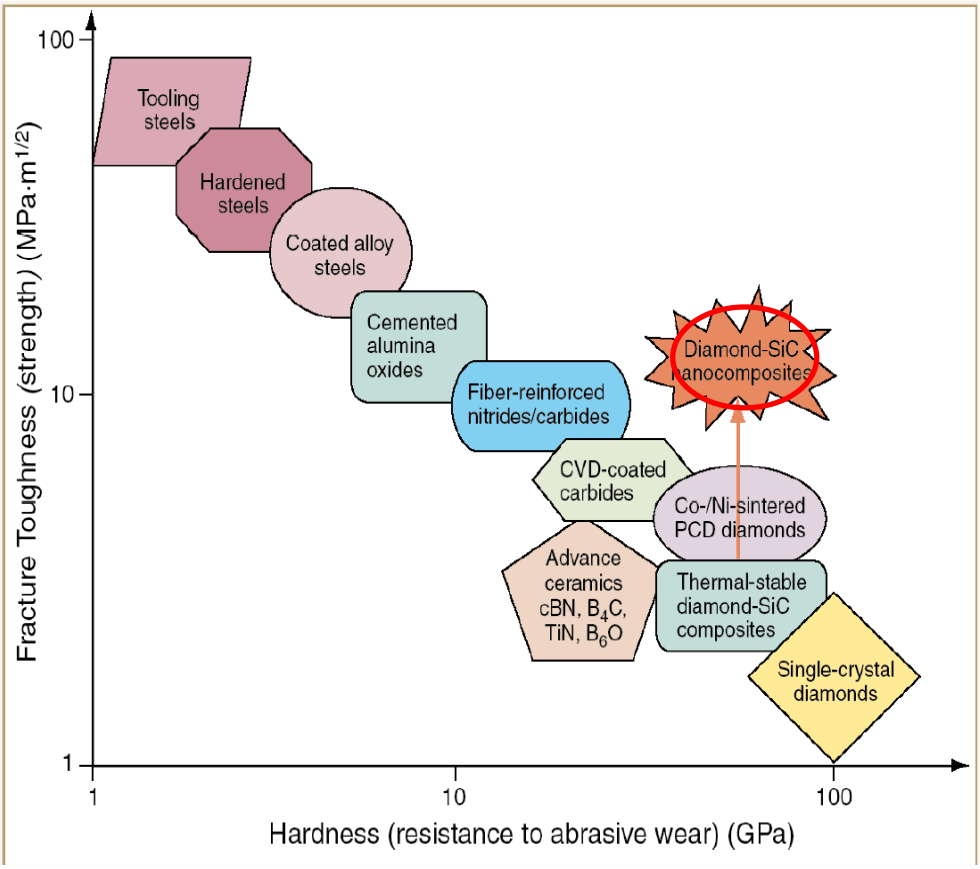

Figure 6. Fracture Toughness vs. Hardness

"Energetics is the application of technology to alter the design of power sources, propulsion and explosive combustibles. It is most commonly associated with increasing their energy density."[42] There is significant motivation to utilize nano-energetic materials in weapon design as these matierials have more surface area per volume than traditional powders and thus perform better when compared to larger materials. Nano-energetic materials enable increased reaction speed, resulting in faster ignition and larger energy releases in a shorter amount of time.

"Nano-energetic materials have shown improved performances in terms of energy release, ignition, and mechanical properties compared to their bulk or micro counterparts."[43] LANL applied these principles to foster the development of nano-explosive reactive munitions (NERM) and materials, such as Tantalum/Bismuth Oxide, incorporating high densities and high-energy densities (Figure 7).[44] Laboratory gas gun results revealed the following:

> Faster reaction rates lead to behaviors not observed in thermites like the ability to generate blast waves and do work. Reaction rates and performance are determined by controlling the particle size and nature of the constitutive particles. As an example, less than 500 milligrams of a composite material with a maximum density greater than steel was initiated and it generated a lethal overpressure in a confined volume.[45]

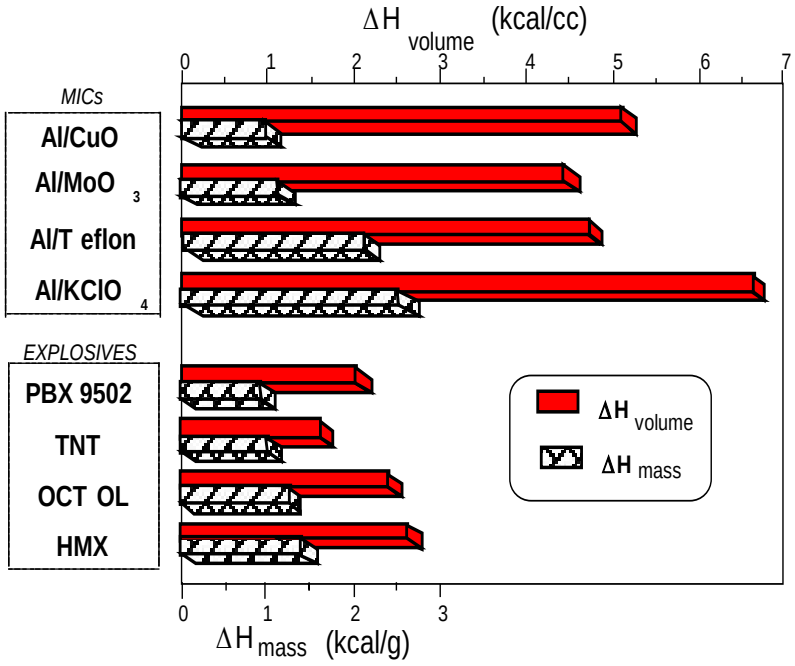

Figure 7. Energy Densities of Composite Energetic Materials vs. Common Explosives

Note the volume of the high melting, organic nitrate explosive (HMX) required to release the same amount of energy as from NERM materials in Figure 8:

Metal	Density g/cm^3	Volume of 400 kg projectile liters	Energy from 30% oxidation MJ	Energy from 5% oxidation MJ	Melting Point ^oC
Hafnium	13.3	30	770	128	2233
Hafnium Carbide	12.2	33	722	120	3000
Tantalum	16.4	24	680	113	3017
Tantalum Carbide	14.3	28	746	124	3880
Tungsten	19.3	21	550	92	3422
Tungsten Carbide	15.6	26	766	128	2785
HMX	1.8	222	700	110	180

Figure 8. NERM vs. Conventional Explosive Materials--Dimensions and Energy Release[46]

For the same explosive power, Scientists anticipate that weapons utilizing nano-energetic materials will be comprised of up to two orders of magnitude less overall mass as conventional weapons.[47] In addition, energetic materials can be designed for a specific application by controlling density and sensitivity to initiation.[48] The Defense Threat Reduction Agency has accomplished extensive work on advanced energetics as well. Near-term efforts include enhanced thermobarics and shock-dispersed fuels. Mid-term efforts emphasize advanced multi-functional energetics and all/high nitrogen species. Far-term efforts include metastable molecular clusters (5 to 50 times greater energy than conventional high explosives (HE)), nuclear spin and shaped isomers (104 times greater than HE), small-scale fusion (108 times greater than HE), and anti-matter annihilation (over 1000 times greater than HE).[49]

Modeling Efforts for Penetrating Weapons and Underground Facilities

As the targets become harder, weapons speed increases and improved materials and energetics are introduced, effective engineering modeling will be essential to evaluating the effectiveness of future HDBT Defeat weapons. For example, HDBT Defeat weapons experience deformations in material and shape as they penetrate a target. Thus, the effectiveness of the

weapon to penetrate the terrain or concrete and release its kinetic energy as designed are adversely affected by such deformations. The survivability of the weapon is dependent the loads on the weapon as influenced by its orientation to the surface, angle of attack, and impact velocity. The construction of the penetrator, to include design and materials, will ultimately control its response to the loads. The depth of the penetration is dependent on the weapon's velocity, mass, and target response.

Current modeling programs are experiencing challenges to modeling the penetration effects on weapons with higher impact speeds and deeper penetrations. Future weapons impacting at hypersonic velocities will experience large scale deformations, only compounding these analytical challenges. In addition, current modeling does not account for the effects of reactive munitions. These include current state-of-the-art Eulerian and Finite Element Modeling programs.[50] LANL has led efforts to create modeling software for accurate weapon lethality analysis at these higher speeds and utilizing reactive munitions.

In order to accurately model the effects of higher velocities on these weapons, LANL scientists recognized the need to combine general purpose hydrodynamic codes that incorporate computational fluid dynamics and computational solid/structural dynamics in three dimensions for various hard materials.[51] In 2009, LANL created a hydrodynamic code coupling both Lagrangian (material motion computed every time step) and Eulerian (rezoning of spatial meshes to original shape/remaining fixed in space).[52] The end result was an Arbitrary Lagrangian/Eulerian (ALE) hydrocode that provides state-of-the-art discrete element modeling (called "CASH") for over 50 material models.[53] The next effort will be to develop a hydrocode that incorporates Dissipative Particle Dynamics: "The basic idea of Dissipative Particle Dynamics is that it should be possible to replace 'blobs' or 'droplets' of fluid with individual

particles which interact in such a way as to reproduce Newtonian hydrodynamics of the fluid as a whole."[54] Incorporation of Dissipative Particle Dynamics will "provide the best means to explore full penetrator and target response regimes (extremely large deformations) expected in hypervelocity impacts."[55] Moreover, modeling the penetration is dependent on an accurate model of the terrain surrounding the HDBT.

There are many sources of intelligence and information that provide only pieces of the picture comprising an underground facility. These include overhead imagery, tunnel/structure geometry, topography, and geology/stratigraphy of the target.[56] However, current Department of Defense geologic models lacked integration of these sources—no three-dimensional model existed for high fidelity shock propagation. LANL scientists created an Interagency Geotechnical Assessment Team to create such a model. The model was to account for complex subsurface geology, optimize the use of available data, and provide high resolution models for numerical calculations. The end-product was the Geologic Assessment Methodology for Underground Targets (GAMUT), providing a way to link site geology and facility information with high fidelity calculators.[57] Though the GAMUT process has undergone successful end-to-end testing, as new fault/fracture modeling is created, this process must be continually updated.

The importance of creating new modeling software for future penetrating weapon capabilities cannot be understated. The development of software algorithms is often the Achilles Heel for emerging military capabilities. Additionally, future reductions in military funding will necessitate even more reliance on software modeling for the development and testing of new military capabilities. Regardless of the many efforts to develop kinetic weapons that will hold HDBTs at risk, the sheer increase in the number of HDBTs may have other implications, especially on the US nuclear posture.

The Nuclear Weapon Debate

The 2010 Nuclear Posture Review stated that although the role of nuclear weapons in US national security and military strategy has been significantly reduced, the US government advocates taking further steps to reduce their role to include total stockpile numbers.[58] However, it emphasizes concerns of a resurgent Russia modernizing its comparable nuclear force and a rising China continuing to quantitatively and qualitatively modernize its nuclear capabilities, while doing so in a non-transparent manner.[59] All of these threats involve nations that continue to enhance and proliferate the capabilities and capacities of their underground facility facilities.

HDBTs are of primary concern when considering the targeting of nuclear weapons. The significant overpressure, ground shock, and electromagnetic pulse effects produced from nuclear weapons make them highly desirable for defeating HDBTs. Moreover, most weapons of mass destruction-related facilities are now constructed as underground. Studies have shown that burn temperatures in excess of 5,000 deg F will neutralize aerosolized chemical and biological agents, as well as functionally defeat weapons of mass destruction processes.[60] As outlined in the 2001 HDBT Report to Congress, "Nuclear weapons have a unique ability to destroy both agent containers and Chemical and Biological Warfare agents."[61] The sole remaining penetrating nuclear weapon in the current US arsenal is the B-61 Mod 11 nuclear bomb, dropped from aircraft directly over-flying the target. As the Air Force responds to changes to future force structure, to include reductions in the nuclear stockpile and other capabilities, it may be forced to consider force structure attributes versus capabilities to ensure effective deterrence and overcome capability gaps.

Such an approach may prompt leadership to revert to a counter-value strategy for targeting nuclear weapons. Since some current HDBTs can only be defeated though the

employment of nuclear weapons, a nuclear counter-value strategy may necessitate greater investment in developing new HDBT defeat technologies that will fill the niche of targets held at risk by nuclear weapons.

Moreover, as countries dig underground facilities deeper in rock terrain, the effects of nuclear weapons are significantly reduced and eventually negated at greater depths. This fact emphasizes the need to expedite the development of advanced penetrating weapons and to continue educating leaders on the coming reductions in effectiveness of current nuclear weapons against future underground facilities. In addition, the 2001 Nuclear Posture Review placed significant emphasis on investments that enable "effective Information Operations targeting, weaponeering, and combat assessment essential to the New Triad."[62] The less effective nuclear and conventional weapons become against deeper underground facilities, the more the need exists for effective Information Operations capabilities against them.

Non-kinetic and Directed Energy Options for Defeating HDBTs

There are other approaches to HDBT defeat that do not involve air or missile delivered kinetic weapons. These include indirect approaches using Information Operations or, perhaps in the future, directed energy. A brief description of each of these capabilities follow.

Information Operations

Joint Publication 3-13 describes Information Operations (IO) as:

> The integrated employment of electronic warfare (EW), computer network operations (CNO), psychological operations (PSYOP), military deception (MILDEC), and operations security (OPSEC), in concert with specified supporting and related capabilities, to influence, disrupt, corrupt, or usurp adversarial human and automated decision making while protecting our own.[63]

There are many underground facilities systems and subsystems that can be affected by the employment of synchronized IO actions. IO actions are applied across physical, informational,

and cognitive dimensions that comprise the information environment. The USSTRATCOM Information Operations directorate, in coordination with the Defense Threat Reduction Agency, continues to investigate new ways to employ IO-related capabilities against HDBTs. These capabilities are associated with attacking and affecting systems internal and external to underground facilities, as well as the personnel and resources that support them. Capabilities related to computer network attack and electronic attack exploit vulnerabilities in computer and electrical systems in order to destroy, disrupt, degrade, deny, deceive, and influence enemy information systems related to HDBTs. Capabilities related to psychological operations specifically target the cognitive and informational dimension of those personnel executing, supporting, and supported by the HDBT's mission. Military deception capabilities and operations can be an enabler for the other IO capabilities as applied against HDBTs.[64] While IO capabilities may prove to be very effective as part of the family of systems for defeating HDBTs, the precise nature and low-yield effect of these non-kinetic capabilities necessitate accurate intelligence of a HDBT, to include its internal and external subsystems, which I have mentioned as problematic.

The primary challenges with executing these capabilities relate to finding system vulnerabilities and gaining access to the target. As adversary nations enhance their A2AD and camouflage, conceal, and deception capabilities, it has made the effective employment of IO and associated capabilities much more difficult. In addition, the ability to disperse and make redundant support systems and subsystems for underground facilities has only compounded this issue. Successful IO against HDBTs may rely heavily on the use of Special Operations when other avenues of attack through connected networks are not available. These operations may require infiltration of Special Forces within close proximity of the facility. Though IO

capabilities and assets that can be effectively employed against some HDBTs exist today, access to and accurate intelligence on these facilities will continue to be problematic. In the quest for advanced capabilities that will not require boots on the ground or the use of high-yield explosives, the use of directed energy weapons against HDBTs has gained considerable emphasis.

Directed Energy Weapons

The development of directed energy weapons has gained increasing importance in the last several years. Their use and effectiveness against underground facilities is debatable, however. Military strategists recognize that many underground facilities derive their military effectiveness through the electronic systems and subsystems that they house. Accordingly, the availability of a counter electronics capability that works against HDBTs is high on the full-dimension defeat wish list.[65]

Development efforts continue for a non-nuclear, directed energy weapon that affects underground facilities systems and subsystems. However, as adversaries dig underground facilities deeper using harder concrete and protect systems against electronic attack, the effectiveness of a directed energy weapon may be limited or completely negated. Thus, as with IO capabilities, directed energy weapons, specifically electromagnetic pulse or High Power Microwave weapons, must target the Achilles heel of HDBTs, such as above ground supporting airshafts, power cabling, heating, ventilation and air conditioning HVAC surface ducts, and access architecture. A multi-shot, multi-target High Power Microwave weapon/aerial platform targeting such electronic systems may be able to effect a mission kill on a HDBT.[66] Once again, the target intelligence must be robust and accurate enough to identify all HDBT systems and subsystems in order to achieve a full-dimensional defeat with directed energy weapons.

Conclusion

The defeat of hard and deeply buried targets has gained much attention in the past year. As recent intelligence updates highlight new adversarial capabilities to enhance underground facilities, they also indicate a growing capability gap in the US military's ability to hold hard and deeply buried targets at risk across the globe. Moreover, further reductions in our nuclear stockpile and continued aging of legacy nuclear penetrating weapons will further reduce kinetic options against HDBTs. Recognizing this gap, many nations continue to construct more advanced underground facilities to protect strategic assets. Such actions have elevated the need to close this gap in our military capabilities as it significantly affects all five operational capability elements (detect, characterize, plan, defeat, and assess) essential to full-dimensional defeat of HDBTs.

The Department of Defense has recognized the need to develop multiple capabilities, kinetic and non-kinetic, to defeat HDBTs. Efforts to establish a roadmap for the creation of a "family of systems" that will defeat HDBTs are currently underway. Understanding that underground facility enhancements and proliferation will continue to be problematic, as well as the ability to detect and characterize them, the 2012 HDBT Analysis of Alternatives must be an end-to-end assessment that not only addresses the means to defeat HDBTs, but also the capabilities necessary to effect all five operational capability elements for full-dimensional defeat. These capabilities must enable holding multiple targets at risk across the spectrum of conflict. Such capabilities will ultimately promote the stability the 2010 Nuclear Posture Review espouses for us to achieve.

Current domestic economic challenges make a leveling of military science and technology (S&T) funding likely for the foreseeable future. In this constrained environment,

continued funding of nanotechnology capabilities that enhance kinetic weapon effectiveness against HDBTs may serve to partially close the HDBT defeat gap. The development of hypersonic delivery platforms is crucial to this endeavor in order to penetrate later generation adversarial A2AD capabilities, as well as provide a standoff capability. Modeling and simulation technologies cannot be overlooked as they set the stage for successful weapon development and are generally the most complex portion of target characterization and weapon development since they are software dependent. Finally, the advancement of non-kinetic and directed-energy capabilities must not be overlooked for the future HDBT Defeat family of systems. However all of these capabilities will continue to be challenged by adversary advancements in anti-access/area denial capabilities, tunneling, concrete hardening, camouflage, conceal, and deception measures, and information sharing in 2035. Thus, the existing HDBT capability gap the US currently experiences may be exacerbated in the future and ultimately force us to consider alternative targets or courses of actions for those vital HDBTs the US cannot hold at risk.

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Notes

[1]Secretary of Defense in conjunction with the Secretary of Energy. *Report to Congress on the Defeat of Hard and Deeply Buried Targets*. Department of Defense, United States of America: July, 2001, p. 8.

[2]Ibid., p. 3.

[3]Gaps related to intelligence collection capabilities against HDBTs, as well as additional information on adversary underground facility capabilities, and findings and recommendations are contained in the 2011 Air Force Scientific Advisory Board study, *Munitions for the 2025+ Environment and Force Structure*.

[4]While the paper points to huge US gaps in intelligence related locating, characterizing, planning, and assessing to underground facilities in its presentation of the problem, the future implications analysis will focus exclusively on target defeat to comply with length and classification limits.

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[9]Ibid., p. XV-5.

[10]Ibid., p. XV-1.

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[14]GlobalSecurity.Org. *Guided Bomb Unit-28 (GBU-28)* [Online] Available. http://www.globalsecurity.org/military/systems/munitions/gbu-28.htm, December 12, 2011.

[15] Battle damage assessments are comprised of information collected on physical and functional damage of the target and target systems as well as on munition effectiveness. Considering the inability of current surveillance and reconnaissance capabilities to conduct accurate post-strike BDA inside underground facilities, weapons themselves must be capable of providing information related to munition effectiveness. Developing this capability for penetrating weapons has proven to be extremely challenging, as has developing effective fuzes that can withstand the extreme forces and deformations the weapon experiences during penetration of the hardened target. Timely and vital BDA of strikes on HDBTs will continue to be a critical capability gap in the foreseeable future. See Sopko, Mark G., Maj. *Air & Space Power Journal*. "Combat Assessment, Analyzing the Results of an Air Campaign." November 15, 1999. [Online] Available**.** http://www.airpower.maxwell.af.mil/airchronicles/cc/sopko.html, February 13, 2012.

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[17]Ibid., slides 40, 43.

[18]GlobalSecurity.org. *BLU-118/B Thermobaric Weapon.* [Online] Available. http://www.globalsecurity.org/military/systems/munitions/blu-118.htm, December 12, 2011.

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[21]Ibid.

[22] Burmeister, Regan E. Briefing. August 19, 2011, slide 178.

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[25]Ibid.

[26]Ibid.

[27]Secretary of Defense. Report to Congress. July 2001, p. 6.

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[29] The roadmap highlights several concerns with continued development of kinetic weapons, to include increasingly complex requirements for test systems, specifically as a result smarter weapons and threat systems, and continuing pressures on test infrastructures due to increasing numbers of test programs. Without addressing these concerns, the rate of development for mid and far term programs will be adversely affected.

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[40]Ibid., slide 6.

[41]Ibid., slides 6-7.

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[43]Ibid., p. 7.

[44]Oldenborg, Richard. Briefing. January 26, 2006, slide 8.

[45]Ibid., slide 8.

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[59]Ibid., pp. 4-5.

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[63]Joint Chiefs of Staff. *Joint Publication 3-13, Joint Doctrine for Information Operations*. February 13, 2006. [Online] Available**.** http://www.dtic.mil/doctrine/new_pubs/jp3_13.pdf, December 12, 2011, p. ix.

[64]Information in this paper related to use of Information Operations (IO) capabilities against HDBTs is based on author's experience as a joint IO planner and Chief of the USPACOM IO Support Team, Joint IO Warfare Command, USSTRATCOM, San Antonio, TX, 2004-2007.

[65]Air Combat Command, Directorate of Requirements. *Enabling Concept for Directed Energy*. Langley AFB, VA: March 24, 2009, pp. 6, 16.

[66]Ibid., pp. 25-26.