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Working Paper

How Much Ballistic Missile Defense Is Enough?

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Abstract

This paper examines how well future U.S. national and theater missile defense systems will have to perform to meet reasonable defense objectives, as a function of the level of the threat. Deploying a thin U.S. national missile defense today is premature because the threat is not readily apparent, the United States can deter most threats, and the United States has some conventional counterforce options against a developing state's nascent ICBM arsenal. However, if, or when, intercontinental ballistic missile threats appear, a defense with 100 interceptors deployed at one or two sites around the continental United States should be able to intercept between 10–20 apparent warheads, assuming NMD systems can detect and track warheads with a probability above 0.99 and that NMD interceptors have a single-shot probability of kill (SSPK) against warheads between 0.35–0.65. Theater-range ballistic missiles present a greater near-term threat. The current THAAD program may provide an effective upper-tier defense, but only if it can achieve detection and tracking probabilities in the range 0.96–0.98 and interceptor SSPKs in the range 0.4–0.65 for threats with between 100–200 apparent warheads. Larger threats will require even higher technical performance. Similarly, the current NTW program will require the same detection and tracking probability, but with interceptor SSPKs in the range of 0.55-0.80 to deal with the same size of threat. Moreover, for these defenses to be truly useful, they must be accompanied by an equally effective lower tier, e.g., using PAC-3 terminal defenses. The main challenge for upper- and lower-tier defenses is responsive threats that use countermeasures such as decoys and chemical or biological submunitions. Airborne boost-phase theater missile defenses are relatively robust with respect to these countermeasures and they pose relatively little threat to the nuclear forces of the five major nuclear powers. Hence, more emphasis should be placed on such systems in current U.S. missile defense plans.

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How Much Ballistic Missile Defense Is Enough?

Introduction

The American debate on ballistic missile defense has often been polarized, with advocates claiming that such defenses are essential to U.S. security and that they should be deployed as soon as possible, and critics claiming that they should not be deployed because they upset strategic stability and/or they won't work.[1] Less frequently does one encounter quantitative analyses of how well defenses would have to work to accomplish specific security objectives. Given the mounting political pressure within the United States to deploy both national and theater missile defenses in the coming decade, this question is of more than academic interest.

Traditionally the question "How much ballistic missile defense is enough?" is addressed by specifying the technical performance associated with a given defense system, then calculating the size of the defense required to meet specific defense objectives. However, the

[1] For earlier articles on the political/military impact of ballistic missile defense see Charles Glaser, "Why Even Good Defenses May Be Bad," *International Security*, Fall 1984, pp. 92–123, and "Do We Want the Missile Defenses We Can Build?" *International Security*, Summer 1985, pp. 25–57; and Keith Payne and Colin Gray, "Nuclear Policy and the Defensive Transition," *Foreign Affairs*, Spring 1984. For more recent articles see Lisbeth Gronlund, George Lewis, Theodore Postol, and David Wright, "Highly Capable Theater Missile Defenses and the ABM Treaty," *Arms Control Today*, April 1994, pp. 3–8; Spurgeon Keeny, Jr., "The Theater Missile Defense Threat to U.S. Security," *Arms Control Today*, September 1994, pp. 3–7; Keith Payne, "Post–Cold War Deterrence and Missile Defense," *Orbis*, Spring 1995, pp. 201–223; Curt Weldon, "Why We Must Act at Once," *Orbis*, Winter 1996, pp. 63–70; and Henry Cooper, "To Build an Affordable Shield," *Orbis*, Winter 1996, pp. 85–100. For good articles on the technical aspects of ballistic missile defense see Richard L. Garwin and Hans A. Bethe, "Anti-Ballistic Missile Systems," *Scientific American*, March 1968; and The American Physical Society Study Group Report on the Science and Technology of Directed Energy Weapons, *Reviews of Modern Physics*, Vol. 59, No. 3, Part II, July 1987.

technical performance of future ballistic missile defense systems is difficult to specify with any certainty. Moreover, plans exist for the size of possible future U.S. ballistic missile defense (BMD) deployments—for example, a national missile defense (NMD) with either 20 or 100 interceptors located at a single site is under study, and theater missile defenses (TMD) with approximately 1,200 Theater High-Altitude Area Defense (THAAD) and/or 650 Navy Theater-Wide (NTW) upper-tier interceptors are currently among the core TMD programs being pursued by the Clinton administration. Therefore, the question is better turned around, namely, "What level of technical performance must defenses meet if existing programs are to meet useful political/military objectives?" For example, how effective must a national missile defense be to provide high-confidence protection against small accidental or unauthorized attacks, or how effective must a theater missile defense be to defend U.S. allies from theater ballistic missiles armed with weapons of mass destruction? This paper addresses these questions.

This paper is divided into four sections. The introduction discusses the ballistic missile and nuclear, biological, and chemical (NBC) weapons proliferation problems, post–Cold War security objectives appropriate for determining how much U.S. ballistic missile defense is enough, the criteria for evaluating defense performance, and generic countermeasures to BMD systems. The second section addresses the question of how much national missile defense is enough for the United States. The third section addresses the same question for theater missile defense, and the last section provides some concluding observations.

Ballistic Missile Threats[2]

NBC weapons are proliferating, albeit slowly, to several states potentially hostile to the United States.[3] Nuclear proliferation has been the dominant concern, although none of the three virtual/de facto nuclear states (i.e., India, Pakistan, and Israel) is likely to come into conflict with the United States, and the four most problematic states from the U.S. perspective (i.e., Iran, Iraq, Libya, and North Korea) are not likely to develop nuclear weapons soon.[4] Chemical and biological weapons (CBW) are of greater concern because

2 The emphasis here on ballistic missile delivery should not be taken to imply that other delivery means, e.g., aircraft, cruise missiles, or covert delivery by truck, ship, foot, etc. are not equally important. In fact, for chemical and biological weapons they may be more attractive delivery means, though ballistic missiles may still be favored by leaders who doubt the effectiveness of covert operations.

3 For a U.S. government assessment of the problem see *Proliferation: Threat and Response*, U.S. Department of Defense, April 1996; and Department of Defense Annual Report to Congress, *Nuclear, Biological, Chemical (NBC) Warfare Defense*, April 1995.

4 Financial and technical problems have set back Iran's nuclear power industry and, presumably, its nuclear weapons program as well, although concern has been raised over Russia's assistance in building several large nuclear power plants in Iran. Iraq's nuclear weapons program was reversed by the 1991 Gulf War and the UN Special Commission's (UNSCOM) efforts to destroy its remaining nuclear weapons infrastructure. Continued monitoring by UNSCOM makes it difficult for Iraq to revive its nuclear program until these inspections cease. Although Libya is interested in acquiring nuclear weapons, it has no indigenous nuclear program. And, North Korea's program was frozen by the Agreed Framework signed in October 1994, although this could unravel.

they cost less to produce than nuclear weapons and the technologies required are dual-use and, hence, difficult to control. The case of Iraq exemplifies the problem since it developed a large clandestine CBW arsenal while evading international scrutiny, used chemical weapons in the 1980–88 Iran-Iraq War as well as against the Kurds in northern Iraq, and continues to hide much of its CBW program despite the most intrusive on-site inspection regime ever implemented.[5]

Ballistic missile proliferation is of concern largely because the modest payloads (typically 500–1,000 kg), short attack timelines (less than 10 minutes for missiles with ranges less than 1,500 km), and the lack of defenses against such missiles make them attractive for delivering nuclear, biological, and chemical weapons.[6] Their relatively poor accuracy—typically 1–2 km circular error probable for missiles with ranges less than 1,000 km—does not appreciably degrade their effectiveness for NBC delivery against large military facilities or urban areas, although it does make them militarily ineffective for conventional attacks.

About 20 states currently either have or are trying to acquire ballistic missiles. Four of these (Iraq, Iran, North Korea, and Libya) were singled out in a 1993 U.S. National Intelligence Estimate as the states most likely to develop intermediate-range ballistic missiles in the next 10 to 15 years.[7] North Korea is particularly troublesome because of its past willingness to sell ballistic missiles abroad, notably the Scud-C and No Dong missiles. Most ballistic missile proliferation to date has involved missiles with ranges less than 600 km.[8] In the next decade, missiles with ranges between 1,000 km and 2,000 km may appear, e.g., North Korea's No Dong-1 and Taepo Dong-1 missiles, Pakistan's Ghauri missile based on the No Dong, and Iran's Shahab-3 and Shahab-4 missiles.[9] After the next decade, missiles with ranges beyond 3,000 km may appear, though they require multistage missiles. While

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Given North Korea's chronic economic problems, a resumption of its nuclear program seems unlikely. However, this relatively benign projection could change rapidly if any of these states acquires nuclear weapons or fissile material by theft or black-market purchase from the former Soviet Union.

5 Evan Medeiros, "Report Says Iraqi Weapons Programs Were More Advanced Than Admitted," *Arms Control Today*, Vol. 25(9), November 1995, p. 21.

6 For an overview of the ballistic missile proliferation problem see Janne Nolan, *Trappings of Power: Ballistic Missiles in the Third World* (Washington, DC: The Brookings Institution, 1991); John Harvey and Uzi Rubin, *Assessing Ballistic Missile Proliferation and Its Control*, Center for International Security and Arms Control, Stanford University, November 1991; and Steve Fetter, "Ballistic Missiles and Weapons of Mass Destruction: What Is the Threat? What Should Be Done?" *International Security*, Vol. 16, No. 1 (Summer 1991), pp. 5–42.

7 See "Prospects for the Worldwide Development of Ballistic Missile Threats, 1993," as reproduced in *The Last Fifteen Minutes: Ballistic Missile Defense in Perspective*, Joseph Cirincione and Frank von Hippel, eds., Coalition to Reduce Nuclear Dangers, 1996, Appendix B.

8 See, for example, "Artillery Rocket, Ballistic Missile, Sounding Rocket, and Space-Launch Capabilities of Selected Countries," *The Nonproliferation Review*, Fall 1996, Vol. 4(1), Center for Nonproliferation Studies, Monterey Institute of International Studies, Monterey, CA, pp. 177–180; and "Theater Ballistic Missile Systems and Capabilities," *Arms Control Today*, March 1996, pp. 29–30.

9 Reports on Iran's Shahab-3 (~1,400 km range) and Shahab-4 (~2,000 km range) missile program have recently appeared in the press. See Bill Gertz, "Russia, China aid Iran's missile program," *The Washington Times*, Sept. 10, 1997, p. 1.

multistage missiles present technical challenges, North Korea recently demonstrated that these challenges can be surmounted when it launched a two-stage Taepo Dong ballistic missile that attempted, but failed, to put a satellite in orbit using a solid-fuel third stage.[10] Moreover, CBW warhead design becomes difficult for missiles with ranges greater than approximately 600 km because reentry heating can destroy CBW agents and atmospheric dispersal becomes difficult at high reentry speeds.

Russia and China are the only two countries that currently field intercontinental-range ballistic missiles that could pose a threat to the U.S. homeland. A controversial 1995 U.S. National Intelligence Estimate, with which the U.S. intelligence community still agrees, stated that no new ballistic missile threats will appear to the 48 contiguous states before 2010, even if some assistance from more advanced states is forthcoming in the form of expertise or hardware.[11] However, a more recent assessment by an independent commission states that long-range missile threats to the United States might develop within as few as five years of a decision to acquire such systems and that little warning may precede operational deployments due to the eroding ability of the U.S. intelligence community to detect such programs.[12] Obviously, without access to much more information, it is difficult to determine which assessment is more accurate. Among the reasons why threats may be more imminent is the increased access to ballistic missile technology, notwithstanding the existence of the Missile Technology Control Regime.[13] Space-launch vehicles are another source of concern because they can be converted to ICBMs, although relatively few states have, or are developing, such vehicles.[14]

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[10] Bill Gertz, "N. Korean missile seen posing risk to U.S.," *Washington Times*, September 16, 1998, pg. 1; Gus Constantine, "N. Korean satellite described as a dud," *Washington Times*, September 11, 1998, pg. 17; and David Wright, "Taepodong 1 test flight," on http://www.fas.org/news/dprk/1998/980831-dprk-dcw.htm September 2, 1998.

[11] This estimate has been challenged by the General Accounting Office, among others. See U.S. General Accounting Office, *Foreign Missile Threats: Analytic Soundness of Certain National Intelligence Estimates*, GAO/NSIAD-96-225, August 1996. On the other hand, an independent review conducted to determine whether the 1995 National Intelligence Estimate was politicized concluded that it was not. In fact, the panel stated that current evidence supports the conclusions reached in the 1995 NIE more strongly than stated in the NIE itself. See Tim Weiner, "Panel Rejects Charges Study Politicized Atom Threat," *New York Times*, Dec. 5, 1996, p. 17.

[12] Donald H. Rumsfeld et al., *Executive Summary of the Report of the Commission to Assess the Ballistic Missile Threat to the United States*, Pursuant to Public Law 201, 104th Congress, July 15, 1998.

[13] For example, China has been accused of violating the Missile Technology Control Regime by selling the M-11 missile (280 km range) to Pakistan and possibly selling the M-9 missile (600 km range) to Syria. There have also been claims that Russian private enterprises, in collusion with Russian government officials, are helping Iran build the Shahab-3 and Shahab-4 missiles, variants of the North Korean No Dong missile, in violation of the MTCR. See Bill Gertz, "Russia, China aid Iran's missile program," *Washington Times*, Sept. 10, 1997, p. 1.

[14] The only states developing space-launch vehicles, besides the five nuclear powers, are Japan, Brazil, India, Israel, and Ukraine. See *The Nonproliferation Review*, Winter 1996, Vol. 3(2), Center for Nonproliferation Studies, Monterey Institute of International Studies, Monterey, CA, pp. 199–202.

If a ballistic missile threat to U.S. territory develops by 2010, besides that posed by Russia or China, it likely will come from North Korea's Taepo Dong-2 missile with a range estimated at 5,500 km if its payload is reduced from 1,000 kg to around 200 kg.[15] With a 5,500 km range, this missile could hit parts of Alaska and the western tip of the Hawaiian Islands. Consequently, this threat would not require a defense of the entire continental United States. Moreover, North Korea might not exist in 12 years. If an intercontinental ballistic missile threat materializes in the developing world, it is unlikely to involve more than a few ICBMs. Recall that China built an ICBM force containing only 10 single-warhead DF-5 ICBMs during the first three decades of its existence as a nuclear power.

Therefore, the ballistic missile proliferation problem largely concerns missiles with ranges less than 2,000 km, potentially armed with NBC weapons, and hence constitutes a threat to U.S. troops overseas and U.S. allies. The ballistic missile threat to the U.S. homeland over the next decade consists largely of the possibility, however remote, of an accidental, unauthorized, or inadvertent attack by Russia or China, and of the possibility that a developing state will acquire long-range missile technology or ICBMs from a more advanced state in contravention of the Missile Technology Control Regime. Finally, if conventionally armed ballistic missiles are the only threat, substantial expenditures for ballistic missile defense would not be justified.

Objectives for Determining How Much Ballistic Missile Defense Is Enough

Appropriate objectives for U.S. national missile defense are to protect against accidental, unauthorized, and inadvertent attacks from Russia (and possibly China) and to protect against small intentional ballistic missile threats from countries to which intercontinental-range ballistic missiles might proliferate in the future. The dissolution of the former Soviet Union and the possibility that Russian leaders might lose control over their nuclear-armed missiles has sparked concern over possible accidental and unauthorized missile launches. The fact that Russia's ballistic missile early-warning network has deteriorated suggests that an inadvertent Russian missile launch in response to false warning of a ballistic missile attack may also be a growing concern.[16] Since it is difficult for the United States to verify that adequate steps have been taken to minimize the likelihood of accidental, unauthorized, and inadvertent ballistic missile attacks, it is not surprising that they have become a popular rationale for a national missile defense. Defenses, after all, are under unilateral U.S. control. Moreover, by potentially limiting the damage from such attacks, defenses reduce the likelihood of further escalation.

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[15] See Lisbeth Gronlund and David Wright, "Threat Assessment, Part A: Third World Missiles," in *The Last Fifteen Minutes: Ballistic Missile Defense in Perspective*, Joseph Cirincione and Frank von Hippel, eds., Coalition to Reduce Nuclear Dangers, Washington, DC, 1996, p. 20; and Bill Gertz, "Intelligence report warns of missile launches against U.S.," *The Washington Times*, May 14, 1996, p. 3.

[16] A recent CIA report apparently raised concerns about the weakness of Russia's ballistic missile early-warning network. See Bill Gertz, "Russian renegades pose nuke danger," *The Washington Times*, October 22, 1996, p. 1.

However, assessing the cost-effectiveness of defenses against accidental, unauthorized, and inadvertent attacks is complicated by the fact that it is virtually impossible to determine either their likelihood or their size. The U.S. intelligence community estimates that "the current threat to North America from unauthorized or accidental launch of Russian or Chinese strategic missiles remains remote and has not changed significantly from that of the past decade."[17] A more recent CIA report allegedly states that under normal circumstances the likelihood of an unauthorized missile launch is "low," despite Russian political and economic turmoil and disarray in the armed forces.[18] While these estimates provide some comfort, it is difficult to know how "remote" or "low" these threats really are. Russian leaders tend to dismiss Western concerns, asserting that Russian nuclear weapons are still under reliable control.[19] How is one to know? Even complete knowledge of the Russian (or Chinese) nuclear command and control system would not allow one to estimate accurately the likelihood of these events.

The likely size of accidental, unauthorized, and inadvertent attacks is also difficult to determine. Accidents may involve only a few missiles. However, the size of unauthorized launches depends on how far up the chain of command one assumes the conspiracy takes place.[20] If field commanders launch ICBMs or SLBMs without authorization, the attack size could range from a few warheads to up to 200 warheads, with most scenarios clustering around 10 warheads for future ICBM forces.[21] If the Russian general staff or commanders of the Strategic Rocket Forces launch missiles without authorization from top political leaders, then large unauthorized attacks involving tens or hundreds of missiles could occur, assuming subordinate commanders carry out their orders.[22] Finally, inadvertent launches,

[17] See Richard Cooper, House National Security Committee Hearings, February 28, 1996, as reproduced in *The Last Fifteen Minutes: Ballistic Missile Defense in Perspective*, Joseph Cirincione and Frank von Hippel, eds., Coalition to Reduce Nuclear Dangers, 1996, Appendix B. See also, Bill Gertz, "Intelligence report warns of missile launches against U.S.," *The Washington Times*, May 14, 1996, p. 3; and "Do we need a missile defense system?" *The Washington Times*, May 14, 1996, p. A15.

[18] See Bill Gertz, "Russian renegades pose nuke danger," *The Washington Times*, October 22, 1996, p. 1.

[19] See Bill Gertz, "Lebed says nuclear problems in Russia pose no global threat," *The Washington Times*, October 24, 1996, p. 11.

[20] For a good treatment of Soviet/Russian nuclear command and control see Bruce Blair, *The Logic of Accidental Nuclear War*, The Brookings Institution, Washington, DC, 1993, Chapter 4.

[21] If Russian launch control officers could circumvent the locks that prevent ICBM launch without being detected and countermanded by higher authorities, these unauthorized launches could involve up to 6–10 missiles, depending on the ICBM silo complex, or up to 9 missiles for an SS-25 battalion involving a total of up to 10 warheads if the ICBMs carry single warheads (as planned under START II), or up to 100 warheads if the missiles carry up to 10 MIRVs (as is the case for the SS-18). If the codes required to launch Russian SLBMs can be circumvented, as many as 16 or 20 SLBMs, depending on the submarine type, carrying a total of between 48 and 200 warheads, might be launched in an unauthorized manner, although future Russian submarines will likely carry fewer warheads.

[22] During the 1991 Russian coup attempt, senior field commanders responsible for Russia's nuclear forces apparently formed a secret pact to disobey any nuclear launch orders coming from the coup plotters. See Bruce Blair, *The Logic of Accidental Nuclear War*, pp. 65–66.

particularly launches based on false warning of an incoming attack, may be quite large, perhaps involving as many as several hundred or several thousand ICBM and SLBM warheads depending on the alert status of Russian forces and whether the START II Treaty enters into force.[23] In summary, the size of accidental, unauthorized, and inadvertent ballistic missile attacks can vary from one to several thousand warheads.

Therefore, the benefit one derives for a given level of ballistic missile defense against accidental, unauthorized, and inadvertent attacks is virtually impossible to determine because the probability and likely size of these attacks are unknown. Other approaches may also reduce the likelihood of these attacks in less expensive ways, e.g., detargeting ballistic missiles, reducing their alert rate, and possibly placing command-destruct packages on ballistic missiles—though the efficacy of these approaches is also difficult to prove.[24] Consequently, protecting against accidental, unauthorized, and inadvertent ballistic missile attacks is a problematic rationale for a thin U.S. national missile defense because one cannot determine how much benefit to expect from different levels of defense, making policy trade-offs virtually impossible. However, this is not to say that one should ignore the problem.

Intentional ballistic missile threats to the U.S. homeland from developing states are not projected to exist before 2010, as discussed above. If they occur, the United States has deterrence and counterforce options for coping with this threat. Deterrence is credible because there is little doubt about the identity of the attacker if ballistic missiles are used—a serious problem for covert attacks—and there is little doubt that the United States would retaliate with conventional or nuclear weapons if the U.S. homeland were attacked with any nuclear, biological, or chemical weapon first.[25] Moreover, against regional opponents, the

[23] Launching Russian missiles before U.S. missiles arrive on target in a hypothetical counterforce attack is an option Russian strategic planners have considered for years. Traditional Soviet writings on the subject emphasized large, prompt retaliatory responses, involving the bulk of the Soviet silo-based ICBM force and SLBMs on pier-side alert. See, for example, Stephen Meyer, "Soviet Nuclear Operations," in *Managing Nuclear Operations*, Ashton Carter, John Steinbruner, and Charles Zraket, eds., The Brookings Institution, Washington, DC, 1987; and Bruce Blair, *Global Zero Alert for Nuclear Forces*, The Brookings Institution, Washington, DC, 1995.

[24] For a proposal calling for dealerting nuclear forces see Bruce Blair, *Global Zero Alert for Nuclear Forces*, Brookings Occasional Paper (Washington, DC: Brookings Institution, 1995). For an interesting proposal for how ballistic missiles might be destroyed after launch see Sherman Frankel, "Aborting Unauthorized Launches of Nuclear-Armed Ballistic Missiles through Post-Launch Destruction," *Science and Global Security*, 1990, pp. 1–20.

[25] There is some debate about the role of nuclear weapons in deterring CBW attacks because this runs counter to U.S. negative security assurances, even if the opponent uses biological or chemical weapons first. While the United States could justify nuclear retaliation according to the legal doctrine of "belligerent reprisal," the United States would have to consider the political consequences of being the first to use nuclear weapons in over 50 years. See George Bunn and Roland Timerbaev, "Security Assurances to Non-Nuclear-Weapon States: Possible Options for Change," *Programme for Promoting Nuclear Non-Proliferation Issue Review*, No. 7, Mountbatten Centre for International Studies, University of Southampton, Southampton, UK, September 1996. For the argument that an ambiguous U.S. declaratory policy should be retained, including the threat to retaliate with nuclear weapons against CBW attacks, see David Gompert, Kenneth Watman, and Dean Wilkening, "Nuclear First Use Revisited," *Survival,* International Institute for Strategic Studies, London, Autumn 1995, pp. 27–44.

United States should be able to destroy first-generation ICBMs with conventional counterforce attacks because these ICBMs typically are launched from fixed sites.[26] Nevertheless, a thin national missile defense could provide insurance against the breakdown of deterrence and ineffective counterforce options. The question is whether the insurance is worth the cost.

Appropriate objectives for theater missile defense are to protect allied cities and U.S. troops from theater-range ballistic missile threats. Protecting allied cities is particularly salient because extended deterrence tends to be less effective than deterrence of attacks against the U.S. homeland, preemptive counterforce attacks are less likely to succeed because theater ballistic missiles are usually mobile, and passive defenses, which are effective for protecting U.S. troops from CBW threats, typically are not available for civilian populations. With respect to nuclear attacks, opponents may be reluctant to use their precious nuclear weapons to attack U.S. military forces unless they believe the threat of attack would make the United States avoid regional intervention altogether or an actual attack would have a significant impact on U.S. military operations. There is reason to believe neither would be true.[27] Instead, they will likely withhold these precious assets to threaten an opponent's cities to deter the defeat of their regime if the war goes badly. This apparently was Saddam Hussein's calculus with respect to CBW use in the 1991 Gulf War. Therefore, the main objective for U.S. theater missile defense should be to protect allied cities so allied leaders are less vulnerable to coercion by opponents possessing ballistic missiles armed with NBC warheads. This is not a favor the United States bestows upon its allies but is required to protect U.S. interests. Protecting U.S. military forces overseas is, to some extent, a lesser included case.

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[26] Recall that Iraq's fixed Scud launch sites were completely destroyed within the first few minutes of the 1991 Gulf War, unlike its mobile Scud launchers. See Barry D. Watts and Thomas A. Keany, *Gulf War Air Power Survey, Volume II: Effects and Effectiveness*, U.S. Government Printing Office, Washington, DC, 1993, pp. 333–334.

[27] Being a status quo power, the United States is apt to be risk averse in many international conflicts. Hence, one would expect nuclear threats from small nuclear powers to be an effective means to deter U.S. intervention. On the other hand, fear of a loss of power, prestige, or influence in the future if the United States appears to have been intimidated by a small nuclear state in the present may strengthen U.S. resolve to intervene to avoid the perception that the United States can be intimidated by small nuclear states. With respect to the impact of nuclear attacks on military operations, typically tens of nuclear weapons (fusion bombs, not fission bombs) are required to blunt large conventional military operations of the sort the United States can mount. The most likely targets for attack would be large, fixed installations such as airfields, ports, command and control centers, and logistics sites, if they can be identified and targeted. Typically around 25–50 such facilities exist in a given theater of operations. For example, in Operation Desert Storm coalition air forces used 23 airfields alone. Moreover, army divisions and ships at sea are difficult to target on the move and some airfields for tactical air operations will be out of range of theater ballistic missiles. Finally, small fission bombs cannot completely destroy some facilities such as large ports, thereby requiring several weapons to render a single facility inoperable. Therefore, small nuclear states cannot expect to defeat U.S. conventional forces with nuclear attacks. Their strategy would have to be to threaten casualties that outweigh the benefits of intervention. But, this is an imprecise threshold and may not be reached by threatening small nuclear attacks, especially if there is reason to believe the attacks will not be carried out (i.e., deterrence will work).

Ballistic Missile Defense Performance Criteria

Determining how much ballistic missile defense is enough depends on the defense performance criterion. Defense performance can be approached from two angles: political and military. As a political matter, defenses must be good enough to satisfy an electorate that national leaders have not forsaken their protection, or to convince allied leaders that the United States is committed to their defense so they are less susceptible to coercion. This may not require high defense performance, as demonstrated by the Patriot TMD system during the 1991 Gulf War.[28] However, from a military perspective ballistic missile defense is useful only if it blocks enough of the attack to make offensive strikes tactically or strategically ineffective. If the targets are cities and the threat involves NBC warheads, the defense performance must be quite high. In this case, it may also have to be quite high to achieve the desired political benefits.[29]

While there is no "correct" defense performance criterion, they must all share the attribute of very low leakage if the defense is attempting to protect targets from weapons of mass destruction. This analysis uses a particularly demanding criterion—a specific probability that no warheads leak through the defense—because such a defense would have clear political and military benefits in a world with nuclear, biological, and chemical threats. Therefore, this analysis assumes a national missile defense must achieve a probability of 0.80 that no warheads leak through the defense for attacks containing up to 10–20 warheads. This is essentially the same performance criterion used by the Ballistic Missile Defense Organization for a U.S. national missile defense.[30] It captures a range of Russian and Chinese accidental and unauthorized launch scenarios, especially if most ballistic missiles contain a single warhead in the future, and covers most intentional threats from countries to which intercontinental-range ballistic missiles might proliferate. For theater missile defense, this analysis assumes a goal of a probability of 0.50 that no warheads leak through the defense, even if the entire theater ballistic missile arsenal is launched at a single target (e.g., an ally's capital). This appears to be less stringent than the NMD criterion. However, one should note that it applies to the opponent's entire theater ballistic missile arsenal, i.e.,

[28] The Patriot system apparently was not effective against Scud missiles, yet it did let Israeli leaders resist public pressure to retaliate for Iraqi missile attacks—an act that would have brought Israel into the war and likely split the U.S.-led coalition.

[29] For example, the political benefit of deploying Patriot batteries to Israel during the 1991 Gulf War may have evaporated quickly had Iraq launched missiles armed with chemical or biological warheads instead of high-explosive warheads.

[30] The official U.S. NMD performance criterion is a "95 percent confidence of a 95 percent kill probability" assuming four interceptors are fired at each incoming object in a shoot-look-shoot mode, with two shots fired in the first shot opportunity and two in the second. See Michael Dornheim, "Missile Defense Design Juggles Complex Factors," *Aviation Week and Space Technology*, February 24, 1997, p. 54. If this criterion is interpreted to mean that the probability of having no more than 1 out of 20 attacking objects leak through the defense is 0.95, this is equivalent to stating that the probability that no warheads leak through the defense is equal to 0.82 for attacks containing up to 10 warheads.

potentially several hundred missiles, instead of a single attack.[31] Such a defense would make theater ballistic missiles tactically useless and strategically marginal.

BMD Countermeasures

The most significant technical advance with respect to ballistic missile defense over the past two decades has been the advent of hit-to-kill interceptors. This is the critical technology upon which most current NMD and TMD systems rely. To date, 20 hit-to-kill intercept tests have been performed against ballistic missile targets, starting with the Homing Overlay Experiment in 1982 and ending with the most recent THAAD test failure on May 11, 1998. In six of these tests the interceptor hit its target. In the rest, some system failure, not necessarily related to the homing warhead, caused the interceptor to miss its target.[32] Despite these tepid test results, there is no physical reason why hit-to-kill interceptors cannot be made to work, although they represent a daunting engineering challenge.

The most important question is not whether hit-to-kill interceptors will work, but rather whether they will work if an opponent deploys countermeasures.[33] Countermeasures can be grouped into three categories: those that make target detection and tracking difficult (thereby delaying the launch of an interceptor or causing it not to be launched at all), those that reduce the interceptor single-shot probability of kill (SSPK) after it is launched, and those that simply overwhelm the defense with too many targets. Examples of countermeasures that make missile and warhead detection and tracking difficult are stealth techniques to reduce their radar and infrared signatures, and radar jammers that increase the background noise. Techniques for reducing exoatmospheric interceptor SSPKs would be cooling the warheads so hit-to-kill infrared seekers have difficulty locking onto their targets (cool

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[31] Several countries may have up to 300 theater-range ballistic missiles in their current arsenals. Iraq reportedly had around 400 Al Hussayn missiles prior to the 1991 Gulf War, though it launched only 88 during the war. See *Jane's Strategic Weapons Systems*, September 1995, Issue 19. However, the number of long-range theater ballistic missiles, e.g., the North Korean No Dong and Iranian Shahab-3 or Shahab-4 missiles, in an opponent's arsenal is likely to be less than 200, at least over the next decade or two. See, for example, "Artillery Rocket, Ballistic Missile, Sounding Rocket, and Space-Launch Capabilities of Selected Countries," *The Nonproliferation Review*, Fall 1996, Vol. 4(1), Center for Nonproliferation Studies, Monterey Institute of International Studies, Monterey, CA, pp. 177–180; and "Theater Ballistic Missile Systems and Capabilities," *Arms Control Today*, March 1996, pp. 29–30.

[32] See Michael Dornheim, "Missile Defense Design Juggles Complex Factors," *Aviation Week and Space Technology*, February 24, 1997, p. 54.; and Bradley Graham, "Low-Tech Flaws Stall High-Altitude Defense," *Washington Post*, July 27, 1998, p. 1.

[33] Relatively little has been published about ballistic missile defense countermeasures. Richard L. Garwin and Hans A. Bethe were among the first to discuss ballistic missile defense countermeasures to early U.S. BMD programs in the late 1960s in "Anti-Ballistic Missile Systems," *Scientific American*, March 1968. A detailed technical treatment of ballistic missile detection, tracking, and decoy discrimination can be found in "Acquisition, Tracking, and Discrimination," Chapter 7, American Physical Society Study Group Report on the Science and Technology of Directed Energy Weapons, *Reviews of Modern Physics*, Vol. 59, No. 3, Part II, July 1987. For a recent update on the countermeasure problem see George N. Lewis and Theodore A. Postol, "Future challenges to ballistic missile defense," *IEEE Spectrum*, September 1997, pp. 60–68.

warheads heat up upon reentry) and encapsulating warheads in large balloons, thereby obscuring the precise warhead location so hit-to-kill interceptors miss their true target.[34] Maneuvering warheads can potentially reduce endoatmospheric interceptor SSPKs. Current BMD designers apparently expect exoatmospheric NMD interceptor SSPKs above 0.65 and TMD interceptor SSPKs as high as 0.80 to 0.85.[35] While this may not be unrealistic for unitary warheads without countermeasures, it is unlikely that such high SSPKs can be achieved in the presence of countermeasures. However, it is also difficult to assess how low the SSPK might drop.

Finally, countermeasures that saturate the defense would be decoys that cannot be discriminated from warheads, MIRVs for nuclear-tipped missiles, chemical and biological warhead submunitions, and large attacks that converge on the defense simultaneously, thereby saturating the tracking and fire-control capabilities of the defense (i.e., saturating the defense "battle space"). Booster fragments can appear as exoatmospheric decoys, although recent advances in radar (e.g., imaging radar with very good range resolution) and optical sensors (e.g., long-wave infrared sensors) may make it possible to discriminate crude decoys and booster fragments from warheads. CBW submunitions are a potential option for theater but not national missile defenses because they cannot withstand the reentry heating associated with long-range missiles. In principle, an adversary could deploy tens or hundreds of CBW submunitions on each theater missile—a threat that will saturate midcourse and terminal theater missile defenses. Small submunitions also will be difficult to track because of their small radar cross section and, if tracked, will be difficult to intercept with hit-to-kill interceptors because of their small size. Finally, one should note that lightweight decoys, e.g., chaff, balloons, etc., would quickly be stripped away by atmospheric drag for missiles with ranges less than approximately 350 km because these missiles never leave the atmosphere.

It is important to note that the current theater ballistic missile threat consists largely, if not solely, of unitary warheads since no intentional countermeasures were used on Iraqi ballistic missiles during the Gulf War and none have been observed in theater ballistic missile tests since then, at least among developing states (although such tests may have gone unnoticed).[36] Nor is it clear when decoys or other countermeasures might appear, although

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[34] Exoatmospheric intercepts occur at altitudes above 80–100 km. Endoatmospheric intercepts occur below this altitude. This distinction is important principally because simple lightweight decoys (balloons, chaff, etc.) are removed from the "threat cloud" at altitudes between 80 km and 100 km, thus reducing the decoy discrimination problem for endoatmospheric intercepts.

[35] See Michael Dornheim, "Missile Defense Design Juggles Complex Factors," *Aviation Week and Space Technology*, February 24, 1997, p. 54. For an estimate of the THAAD SSPK equal to 0.80 see "THAAD," *World Missiles Briefing*, Teal Group Corporation, Fairfax VA, 1996, p. 6. Using the NMD performance criterion stated by the Ballistic Missile Defense Organization one can infer that NMD interceptor SSPKs must be above 0.65.

[36] The Rumsfeld Commission recently pointed to weaknesses in the U.S. Intelligence Community's ability to accurately monitor ballistic missile development programs. Presumably this includes an opponent's countermeasure programs. While flight tests of modestly sophisticated countermeasures probably would be necessary, they may be difficult to observe. Recall the recent North Korean Taepo Dong-1missile launch that attempted to put a satellite into orbit. The inability to determine whether this was a satellite launch, as North Korea originally claimed, or a ballistic missile test highlights the difficulty in providing accurate monitoring to

it seems reasonable to assume they will because these countermeasures, while not trivial, are probably within the reach of most countries that have the ability to produce ballistic missiles indigenously.

A definitive technical assessment of these countermeasures and BMD counter-countermeasures is beyond the scope of this paper. Suffice it to say that the effectiveness of BMD systems against simple threats (i.e., unitary warheads with only crude penetration aids) may be fairly good, assuming adequate testing can solve the engineering problems that plague current-generation hit-to-kill interceptors. However, BMD effectiveness against future threats is uncertain and will depend largely on the ability to defeat offensive countermeasures of the sort mentioned above. If midcourse and terminal countermeasures prove difficult to defeat for upper and lower-tier TMD systems, then airborne boost-phase TMD systems become attractive because they are relatively robust to enemy countermeasures. For example, they are the only active defense capable of defeating CBW submunitions, unless one considers nuclear-tipped TMD interceptors—a politically unattractive option for the United States, although some Russians have expressed interest in such systems. The impact of countermeasures is captured in the following analysis by analyzing the variation in defense effectiveness as a function of parametric variations in the warhead detection and tracking probability, the interceptor SSPK, and the number of decoys that cannot be discriminated from warheads.

How Much NMD Is Enough?

Currently only two states, Russia and China, can threaten the United States with intercontinental-range ballistic missiles. Moreover, it is unlikely that any other states hostile to the United States will deploy ICBMs before 2010, unless they are aided by more technically advanced states. If, or when, such threats appear, deterrence should be effective in most scenarios—accidental, unauthorized, and inadvertent attacks being a notable exception—and U.S. preemptive conventional counterforce attacks should be effective against the fixed ICBMs developing countries might deploy. If accidental, unauthorized, and inadvertent attacks from Russia (or China) are the dominant concern, their likelihood may be reduced by other, relatively inexpensive, means. Therefore, there is no compelling need to deploy a thin national missile defense at the current time, although research and development on national missile defense is a prudent hedge in case threats arise in the future. Consequently, the short answer to the question "How much national missile defense is enough?" is "None."

However, if threats arise in the future, it is useful to note that a thin national missile defense consisting of 100 ground-based interceptors deployed at several sites around the United States might provide protection against small accidental and unauthorized ballistic

observe the deployment of countermeasures, especially on short and medium-range ballistic missiles, even when the U.S. Intelligence Community has advance notice of the launch.

missile attacks containing up to 10–20 apparent warheads, and provide some insurance against the failure of deterrence and conventional counterforce options if regional opponents acquire a few ICBMs, as the subsequent analysis will show. The ABM Treaty would have to be amended to allow such a defense, but this would not necessarily undermine strategic stability. Even a single-site defense with 100 interceptors probably violates the ABM Treaty because, although 100 interceptor launchers are allowed at a single site and there is no speed limit on ABM interceptor missiles, the 100-interceptor exception in the ABM Treaty (i.e., Article III) was intended to allow a thin defense of an individual region and not a defense of a country's entire territory.[37] If a single-site NMD system is deployed at a site that is not around the nation's capital or one of its ICBM fields, or if multiple sites are deployed for a more robust national missile defense, then clearly the ABM Treaty would have to be amended or abrogated.

Two issues must be addressed to calculate how much national missile defense is enough to guarantee that all warheads in an attack will be destroyed with a probability of at least 0.80: the number of sites required to cover the United States and the number of interceptors required at each site to meet the defense performance criterion as a function of the attack size. The number of NMD sites required to defend the United States depends on the area that can be defended from a single site, i.e., the defended footprint.[38]

If the initial system is to be ABM-Treaty compliant, the initial site must be located at Grand Forks, North Dakota, or around Washington, D.C. From Grand Forks an interceptor with a burnout speed above 6.5 km/sec and supported by space-based tracking sensors can cover the entire continental United States for northerly attacks (i.e., Russian ICBMs and SLBMs launched from their bastions or Chinese ICBMs) with a barrage firing doctrine but not with a shoot-look-shoot doctrine because less time is available for the second intercept attempt.[39] Two sites would be required for barrage coverage of attacks from all azimuths.

[37] Article I, paragraph 2 of the ABM Treaty clearly states that "Each Party undertakes not to deploy ABM systems for a defense of the territory of its country...and not to deploy ABM systems for *a defense of an individual region except as provided for in Article III* of this Treaty" (emphasis added). Article III allows up to 100 ground-based interceptor launchers at a single deployment area whose radius is less than 150 km centered either on the nation's capital or one of its ICBM silo fields. In addition, it specifies constraints on the number of ABM radars that can be located at that site. Article III clearly is intended to allow a thin regional ABM defense and not one that covers the entire national territory.

[38] The defended footprint depends on the interceptor design, the warhead signature (i.e., radar cross section and infrared radiated power), and the character of the sensor support (i.e., the radar power-aperture product, the infrared optics, and the location of the sensors, e.g., ground-based radars collocated with the NMD interceptors, ground-based radars located elsewhere within the continental United States or outside U.S. territory, or space-based infrared sensors such as the Space-Based Infra-Red Sensor–Low-Earth Orbit, or SBIRS-LEO system). SBIRS-LEO, formerly known as the Space and Missile Tracking System (SMTS) and before that Brilliant Eyes, is a constellation of low-earth-orbit satellites designed to track objects in space using long-wave infrared sensors.

[39] In a barrage firing doctrine several interceptors are fired at the incoming warhead nearly simultaneously. In shoot-look-shoot mode the defense initially fires one or two interceptors at each warhead, then fires a volley of interceptors at any warhead that leaks through the first shot opportunity. Shoot-look-shoot firing doctrines are

Finally, two sites would be required to cover the entire continental United States with a shoot-look-shoot firing doctrine for northerly attacks, whereas four to nine sites would be required to cover threats from all azimuths depending on the track data that can be obtained during the early midcourse portion of a ballistic missile's trajectory (i.e., depending on whether ground-based radars located outside the continental United States or space-based tracking sensors are employed).[40] Alaska and Hawaii may fall within the outer reaches of West Coast NMD sites but, more likely, would be protected by short-range missile defenses that provide local coverage.

The number of NMD interceptors required at each site can be derived using a simple model wherein the technical performance of the defense is captured by two parameters: the probability with which the NMD sensors can successfully detect, track, and classify incoming warheads as warheads so an interceptor can be launched against them, labeled here as *P(track)*, and the probability with which a single interceptor can destroy an incoming warhead (i.e., the interceptor SSPK).[41] Again, for this analysis, the size of the defense is specified in advance and the technical performance that such a defense must meet is calculated. This approach has been taken because reliable estimates for the technical performance of future NMD systems are difficult to obtain, in part because this requires detailed technical information regarding the exact NMD architecture (which has yet to be finalized), the guidance system of the interceptors, the physical signatures of ballistic missile warheads, and the effectiveness of possible countermeasures, and in part because historical experience leads one to be cautious about accepting the design performance of BMD systems as indicative of their actual wartime performance.[42]

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more efficient because subsequent interceptors are not launched if the warhead is destroyed in the first shot opportunity. However, they are more demanding technically because they require confident kill assessment after the first shot and they have smaller defended footprints because less flyout time is available for the second intercept attempt.

[40] See Russell Shaver, "Priorities for Ballistic Missile Defense," in *New Challenges for Defense Planning: Rethinking How Much Is Enough*, ed. Paul Davis, RAND, Santa Monica, CA, 1994, pp. 280–281.

[41] For a description of this model see Dean A. Wilkening, *A Simple Model for Calculating Ballistic Missile Defense Effectiveness*, CISAC Working Paper, Center for International Security and Cooperation, Stanford University, Stanford, CA, August 1998.

[42] Historical experience, especially regarding Patriot performance in the 1991 Gulf War, suggests that one should not be overconfident about the technical performance of BMD systems. The U.S. Army maintains that Patriot batteries were responsible for successfully intercepting over 40 percent of the Scuds fired at Israel and over 70 percent of those fired at Saudi Arabia. However, the true intercept rate was probably below 10 percent and may have been closer to zero. See Henry L. Hinton, *Operation Desert Storm: Data Does Not Exist to Conclusively Say How Well Patriot Performed*, U.S. General Accounting Office, GAO/NSIAD-92-340, September 1992; George N. Lewis and Theodore A. Postol, "Video Evidence on the Effectiveness of Patriot during the 1991 Gulf War," *Science and Global Security*, Vol. 4, 1993, pp. 1–63; and Jeremiah Sullivan, Dan Fenstermacher, Daniel Fisher, Ruth Howes, O'Dean Judd, and Roger Speed, *Technical Debate over Patriot Performance in the Gulf War*, Arms Control, Disarmament, and International Security Research Report, University of Illinois at Urbana-Champaign, 4 April 1998.

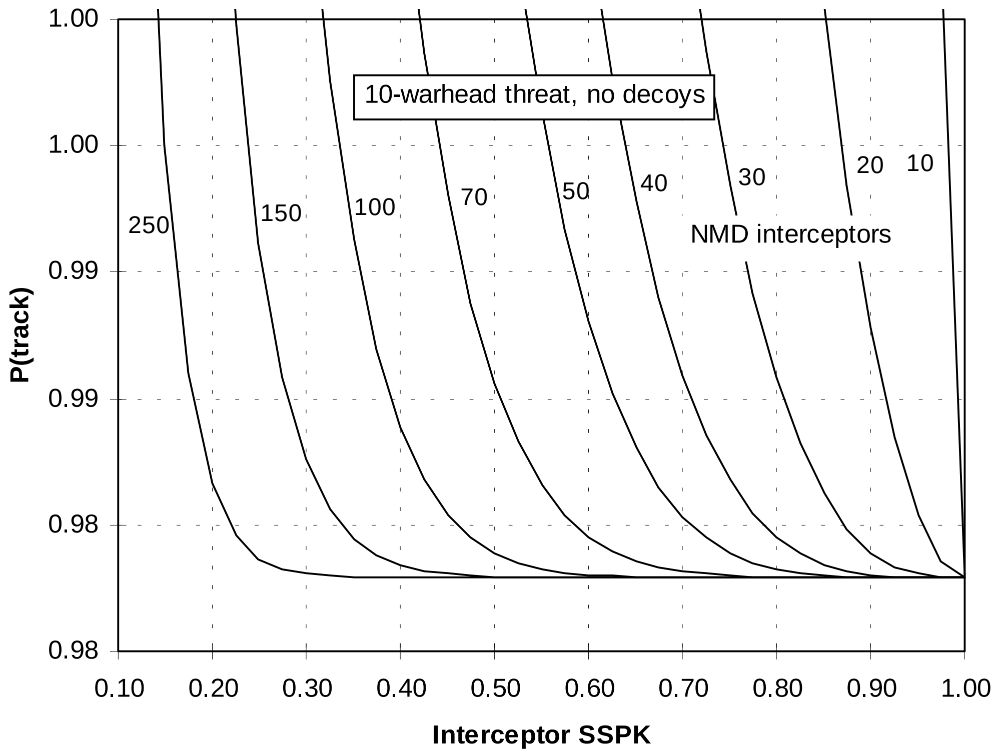

Fig. 1 - NMD Interceptors (Barrage) vs. 10-Warhead Threat

Figure 1 illustrates how the number of NMD interceptors that must engage the attack varies as a function of interceptor SSPK and warhead detection and tracking probability for a fixed attack size containing 10 warheads. This figure assumes a barrage firing doctrine.[43] Note that the defense cannot meet the performance criterion if *P(track)* is below 0.978, for this attack size, regardless of the interceptor SSPK or how many shots are fired. Two concepts currently under discussion for an initial single-site NMD system have either 20 or 100 NMD interceptors deployed at Grand Forks or possibly at another location, e.g., Alaska, the latter of which would require modifying the ABM Treaty.[44] Therefore, the required technical performance for 20-interceptor and 100-interceptor defenses corresponds to any values of SSPK and *P(track)* to the right of the 20-interceptor and 100-interceptor contour lines, respectively. Note that if the SSPK drops below 0.50, the required number of interceptors begins to grow rapidly, making an effective defense increasingly implausible

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[43] For a barrage firing doctrine the number of shots taken at each warhead is constant along each of the NMD interceptor contour lines, e.g., four shots are taken at each target along the 40-interceptor contour line.

[44] See U.S. General Accounting Office, *National Missile Defense*, GAO/NSIAD-98-153, Washington, D.C., June 1998, pp. 12–14; and Stanley Kandebo, "U.S. Pursues NMD System to Prepare for 'Rogue' Threat," *Aviation Week and Space Technology*, March 3, 1997, pp. 44–45.

because six or more shots must be fired at each incoming warhead.[45] Again, current NMD planners hope to achieve SSPKs above 0.65.[46]

Figure 1 illustrates the size of the defense assuming all interceptors can engage the incoming warheads. This would be true, for example, if high-speed interceptors are fired in a barrage from a single NMD site or for a multisite NMD system where the attack is allocated against targets spread uniformly throughout all defended areas, as might be the case for an accidental or unauthorized attack. However, if an attack is concentrated against targets located in a subset of the defended areas for a multisite NMD system, then proportionately more interceptors than shown in Fig. 1 must be deployed to meet the defense performance criterion.[47]

Figure 2 illustrates similar variations for a shoot-look-shoot firing doctrine, again for an attack containing 10 warheads.[48] The optimal number of shots taken in the first shot opportunity varies across the domain.[49] Multiple sites are required to cover the continental United States for a shoot-look-shoot firing doctrine. Hence, the total number of interceptors that must be deployed is equal to the numbers in Fig. 2 only if the attack is spread uniformly over all defended areas. If the attack is concentrated against targets located in a subset of the defended areas to saturate the defense, then proportionately more interceptors must be deployed, as discussed above for a barrage firing doctrine. Therefore, for example, if an attack with 10 warheads is directed against targets located in the non-overlapping region of one shoot-look-shoot footprint for a four-site system, four times the number of interceptors shown in Fig. 2 would be required nationwide to guarantee that no warhead would leak though the defense.

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[45] Taking more than six shots at each incoming object may saturate the NMD battle space because each interceptor must be tracked as it flies toward the intercept point. The defense may also limit the number of interceptors allocated to each early-arriving warhead to allow for subsequent attacks, assuming the attack is believed to be intentional. While these argument are suggestive, they do not set rigid limits on the number of shots an NMD system can take at each incoming warhead.

[46] See footnote 35.

[47] In general, the number of interceptors that must be deployed is equal to the ratio S/N times the numbers given in Fig. 1, where S is the number of sites required for complete coverage and N is the number of sites that can engage the incoming attack. For example, if two sites are required for barrage coverage and the attack is concentrated against targets located in a single defended area, then twice the number of interceptors shown on the contour lines in Fig. 1 must be deployed to guarantee that 10 out of 10 warheads can be shot down with a probability of 0.80, i.e., the technical performance required for a 100-interceptor defense would be values of SSPK and *P(track)* to the right of the 50-interceptor contour line in Fig. 1.

[48] For a shoot-look-shoot doctrine, the number of shots taken at each warhead is not constant along the interceptor contour lines in Fig. 2.

[49] Typically, one shot taken in the first shot opportunity approximately between the 10-interceptor and 25-interceptor contour lines, two shots in the region between the 25-interceptor and 40-interceptor contour lines, three shots between the 40-interceptor and 100-interceptor contour lines, and four or more shots to the left of the 100-interceptor contour line. For a derivation of the optimal shoot-look-shoot interceptor allocation see Dean A. Wilkening, *A Simple Model for Calculating Ballistic Missile Defense Effectiveness*, op cit., pp. 16–20.

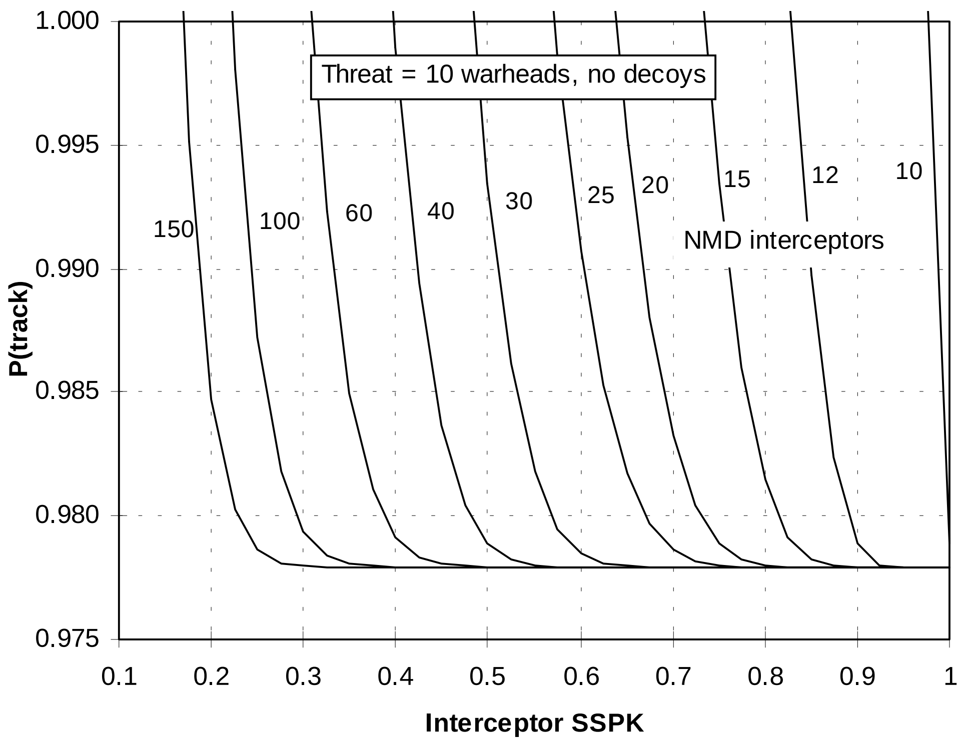

Fig. 2 - NMD Interceptors (Shoot-Look-Shoot) vs. 10-Warhead Threat

If such a four-site defense operates in a barrage firing mode, the defended footprints become approximately twice the size of the shoot-look-shoot footprints, thereby increasing the overlap between adjacent sites. In this case, the Midwest could be defended by interceptors fired in a barrage from any of the four sites and the East and West coasts would be covered by interceptors from two of the four sites. Consequently, the total number of interceptors that must be deployed for a four-site NMD architecture to handle the worst-case attack scenarios would be at most twice the numbers given in Figure 1 for a barrage firing doctrine and four times the numbers given in Fig. 2 for a shoot-look-shoot doctrine. For example, 100 NMD interceptors deployed at four sites can guarantee with a probability of 0.80 that no warheads will leak through a defense operating in barrage mode provided the technical performance of the defense is to the right of the 50-interceptor contour line in Fig. 1 and to the right of the 25-interceptor contour line in Fig. 2 if the defense operates in shoot-look-shoot mode. Note that this is essentially the same technical performance for either mode, at least for small threats. This raises the question of whether operating the defense in shoot-look-shoot mode is desirable because the increased efficiency of the shoot-look-shoot mode is offset by the decreased coverage for attacks that are concentrated to saturate the defense. Moreover, shoot-look-shoot doctrines require accurate kill assessment, which may be technically difficult to achieve. Hence, operating in barrage mode appears to be the best option for a thin national missile defense, at least for small threats.

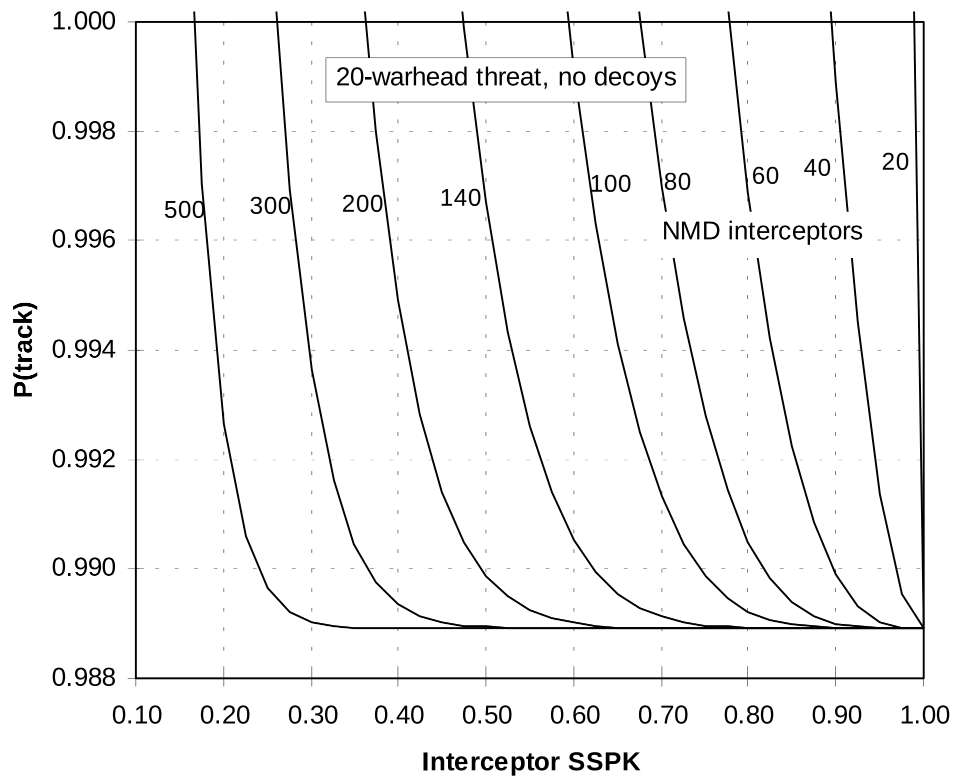

Fig. 3 - NMD Interceptors (Barrage) vs. 20-Warhead Threat

Figure 3 illustrates the number of NMD interceptors required to meet the defense performance criterion for a barrage firing doctrine assuming a 20-warhead threat. As one can see, better detection and tracking probabilities and higher SSPKs are required as the number of warheads in the threat increases. In particular, a 100-interceptor single-site NMD system would have to have values for SSPK and *P(track)* to the right of the 100-interceptor contour line in Fig. 3, e.g., an SSPK above 0.65 and a detection and tracking probability above 0.994.

Until now, this discussion has assumed that decoys are not present or that NMD systems can discriminate warheads from decoys. The latter may not be a realistic assumption, except possibly for crude decoys. Hence, the number of apparent warheads with which the defense must contend may be several times the number of real warheads. Figures 1–3 can also be used to size the defense if decoys are present in the attack. In this case, the fixed attack size in these figures represents the number of real warheads in the attack (i.e., 10 or 20 warheads). The number of NMD interceptors along each contour line must be multiplied by the ratio of the number of apparent warheads (i.e., warheads plus decoys that cannot be discriminated by the defense) to the number of real warheads in the attack to obtain the correct number of interceptors required to meet the defense performance criterion.[50] For example, if two undiscriminated decoys accompany each warhead in a 10-warhead attack directed against a single-site NMD system operating in barrage mode, then a 100-interceptor defense would have to have an SSPK and a warhead detection and tracking probability to the right of a 33-interceptor contour line in Fig. 1 to be able to shoot down all 10 real warheads from among 30 apparent warheads with a probability of 0.80 (e.g., an interceptor SSPK above 0.75 and a warhead tracking probability above 0.99).[51] Note that the number of interceptors required grows linearly with the apparent attack size.

In summary, a modified ABM Treaty that allows the United States or Russia to deploy 100 interceptors at one or more sites should provide adequate protection against attacks containing fewer than 10 warheads aimed at targets spread evenly throughout all defended areas, provided NMD interceptors can attain SSPKs above 0.35 and warhead detection and tracking probabilities above 0.99. For such small threats, shoot-look-shoot doctrines probably are not worth the cost because a barrage firing doctrine works equally well, thereby avoiding the problem of reliable kill assessment. If effective decoys are added to the threat, the interceptor SSPK must increase, but not the detection and tracking probability, to meet the same performance criterion. If the attack is concentrated against a subset of the defended areas for a multisite defense, proportionately more interceptors would be required to meet the defense performance criterion. For attacks containing more than 20 warheads, NMD systems will either require in excess of 100 interceptors, interceptor SSPKs above approximately 0.70 and detection and tracking probabilities above 0.99, and/or effective decoy discrimination. Since 100 NMD interceptors might provide an adequate defense against attacks containing up to 20 apparent warheads, assuming a high level of technical performance, it is not worth the political costs to modify the ABM Treaty to allow more interceptors at the current time, given that concerns likely will arise with respect to the retaliatory capabilities of the medium nuclear powers.[52] Modifying the treaty to allow multiple sites may be more useful and should be easier to accomplish politically.

Finally, a thin national missile defense consisting of 100 interceptors would have an acquisition cost of approximately $7.5 billion (1997 dollars) if deployed at a single site and

[50] To be precise, this is true only for barrage firing doctrines. It is also true for shoot-look-shoot firing doctrines if the interceptor SSPK against warheads is the same as for decoys, which in general will not be the case. For the more general calculation see Dean A. Wilkening, *A Simple Model for Calculating Ballistic Missile Defense Effectiveness*, op cit., p. 17.

[51] The example of two high-quality decoys per warhead is motivated by the fact that Great Britain reportedly had two high-quality decoys, in addition to other penetration aids, for each Chevaline warhead deployed on British Polaris SLBMs in the 1980s. See Robert Norris, Andrew Burrows, and Richard Fieldhouse, *British, French, and Chinese Nuclear Weapons*, *Nuclear Weapons Databook*, Vol. V, Westview Press, 1994, pp. 105–113.

[52] For an analysis of this impact see Dean A. Wilkening, *How Much Ballistic Missile Defense Is Too Much?* CISAC Working Paper, Center for International Security and Cooperation, Stanford University, Stanford, CA, October 1998.

around $20 billion if these interceptors are spread around four sites.[53] If the single site is located at the Grand Forks Minuteman ICBM site and the interceptors are refurbished Minuteman III ICBMs, then the total acquisition cost might drop to around $5 billion for 100 interceptors.[54] Estimates for alternative NMD architectures have been as high as $60 billion (1994 dollars).[55] A more recent estimate places the total 20-year life cycle cost (i.e., R&D, acquisition, and operating costs for 20 years) for a single-site NMD system at $18.4–$28.3 billion, depending on when and where the system is deployed.[56]

Therefore, although the short answer to the question "How much national missile defense is enough?" is "None," if threats become apparent in the future, a thin NMD system consisting of 100 interceptors located at one or two sites should be sufficient provided the threat is smaller than 10–20 apparent warheads and the defense can achieve warhead detection and tracking probabilities above 0.99 and NMD interceptor SSPKs above 0.4–0.75. Only if the projected intercontinental ballistic missile threat to the United States is larger than 20 apparent warheads, deterrence and conventional counterforce options against nascent ICBM arsenals are deemed ineffective, and alternatives for reducing the likelihood of accidental, unauthorized, and inadvertent attacks are nonexistent or too expensive should one consider deploying a national missile defense substantially in excess of 100 interceptors.

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[53] This estimate is based on the Army proposal for a single-site national missile defense consisting of new ground-based radars, 20 interceptors, command and control systems, and a new base infrastructure. The estimated cost is around $5.0 billion, of which $4.5 billion is associated with each site and around $25 million is the cost for each interceptor. Using this estimate, one arrives at an estimate of $7 billion (1996 dollars) for 100 interceptors deployed at a single site and $20.5 billion if 100 interceptors are deployed at four sites. See USAF White Paper, *Minuteman Option for National Missile Defense*, Department of the Air Force, USAF/XOXI, June 1996. An estimate of $7.5 billion (1997 dollars) for 100 interceptors at a single site is also given by Stanley W. Kandebo, "U.S. Pursues NMD System to Prepare for 'Rogue' Threat," *Aviation Week and Space Technology*, March 3, 1997, p. 44.

[54] The U.S. Defense Department recently estimated that the acquisition cost would be $4.0 billion for an initial NMD site at Grand Forks, ND, consisting of 20 interceptors using refurbished Minuteman ICBM boosters with an exoatmospheric-kill vehicle as payload, existing ICBM silos, and the existing base infrastructure. If one assumes $3.5 billion of this is for base improvements and that it costs around $15 million for each refurbished Minuteman interceptor (including the exoatmospheric-kill vehicle), then a 100 interceptor deployment would cost around $5 billion. See John Donnelly, "Minuteman Missile Defense Would Cost $4 Billion," *Defense Week*, June 2, 1997, p. 3. An earlier Air Force estimate using a less expensive kinetic-kill vehicle set the cost at $2.4 billion. See USAF White Paper, *Minuteman Option for National Missile Defense*, Department of the Air Force, USAF/XOXI, June 1996.

[55] The Congressional Budget Office estimated that it would take between $30 and $60 billion to deploy a national missile defense system of the sort called for in the 1996 Defend America Act, i.e., one that included space-based lasers, space-based sensors, and ground-based interceptors and radars deployed at several sites around the United States. In addition it would cost around $2–$4 billion annually to operate such a defense. See Jeff Erlich, "Group Adds Billions to NMD Cost Estimate," *Defense News*, August 5–11, 1996, p. 4.

[56] The low cost estimate pertains to a system deployed at Grand Forks in 2003 and the high estimate is for a system deployed in Alaska in 2006. The later deployment date allows more interceptors and space-based tracking sensors to be included in the system architecture. See U.S. General Accounting Office, *National Missile Defense*, GAO/NSIAD-98-153, Washington, DC, June 1998, pp. 12–14.

Theater Ballistic Missile Defense

Current TMD Programs

The "core" TMD programs currently funded by the Ballistic Missile Defense Organization include the Patriot PAC-3 system, the Navy Area Defense (formerly Navy lower tier), the Theater High-Altitude Area Defense (THAAD), the Navy Theater-Wide defense (formerly Navy upper tier), and the Medium Extended Air Defense System (MEADS).[57] PAC-3 is a lower-tier defense using the Erint interceptor which will begin deployment by the end of 1999. The Erint interceptor is a new agile missile with a hit-to-kill warhead designed to intercept targets up to approximately 30 km in altitude. The total PAC-3 program is projected to contain around 1,200 Erint missiles, a number sufficient to outfit 25 Patriot batteries with 48 missiles each. The total program cost (i.e., development plus procurement costs) for the Patriot PAC-3 system is estimated to be $7.4 billion.[58]

The Navy Area Defense (NAD) is a lower-tier defense using a blast-fragmentation warhead and a modified version of the Standard Missile-2 (the Block 4A) currently deployed on Aegis cruisers for air defense. Although the full program for NAD has yet to be defined, the current plan is to buy more than 1,500 Block 4A missiles, with production starting around 2002, to be deployed in the vertical launch systems aboard at least 22 Aegis cruisers and 18 destroyers.[59] The total NAD program cost is projected to be $6.2 billion.[60]

THAAD is an upper-tier defense designed to engage ballistic missile warheads at altitudes between 40 km and 150 km. THAAD is based on a hit-to-kill interceptor with a flyout speed around 2.5 km/sec and an infrared seeker.[61] The THAAD ground-based radar is reputed to

57 TMD systems can be categorized according to the altitude at which they make their intercepts. Defenses that intercept targets below 40 km are called lower-tier systems. In this region aerodynamic forces are appreciable, causing most decoys to be stripped away, thereby making decoy discrimination easier but potentially causing the warheads to maneuver due to aerodynamic forces, making them hard to intercept. The defended footprint for lower-tier systems is small and shoot-look-shoot tactics are not possible because insufficient time remains for reliable kill assessment and a second shot. TMD interceptors that intercept their targets above 40 km are called upper-tier defenses. Between 40 and 80–100 km, the upper-endoatmospheric region, atmospheric forces are too weak for warhead maneuvering, but light decoys are stripped away. In this region, the defended footprint grows and shoot-look-shoot tactics become possible. Finally, above around 80–100 km the effects of the atmosphere are negligible. In the exoatmospheric region, TMD systems must cope with the full range of decoys that might accompany an incoming warhead, making decoy discrimination the principal technical challenge. Large defended footprints and shoot-look-shoot tactics, in principle, are possible.

58 See John Pike, "Ballistic Missile Defense: Is the U.S. 'Rushing to Failure?'," *Arms Control Today*, Vol. 28, No. 3, April 1998, pg. 11.

59 See David Hughes, "Navy Readies Fleet for Anti-Scud Warfare," *Aviation Week and Space Technology*, February 24, 1977, pp. 61–63; and "Navy Tactical Missile Defense," *World Missiles Briefing*, Teal Group Corporation, Fairfax, VA, 1996.

60. See John Pike, "Ballistic Missile Defense: Is the U.S. 'Rushing to Failure?'," op cit., pg. 11.

61 See Michael Dornheim, "Thaad Program Future Tied to Test Results," *Aviation Week and Space Technology*, March 3, 1997, pp. 64–65.

be a powerful phased-array X-band radar with a nominal detection range up to 500 km that can discriminate simple decoys based on their size and radar cross section. The THAAD program currently consists of 14 radars and 1,233 THAAD missiles.[62] The total THAAD program cost is projected to be $17.9 billion.[63] Deployment of the first operational battery was recently accelerated from 2006 to 2004, though the program may slip or be canceled entirely if the THAAD test program is not successful (all five tests to date have failed).

The Navy Theater-Wide (NTW) defense is an upper-tier defense and is the least mature of the core TMD systems. Neither the missile nor the warhead design has been finalized. Typically, a boosted Standard Missile-2 is assumed with a burnout speed around 4–4.5 km/sec. The warhead most frequently assumed is the hit-to-kill Lightweight Exo-Atmospheric Projectile (LEAP). Since LEAP uses long-wave infrared sensors it can only operate outside the atmosphere (reportedly above 70 km).[64] Currently 650 NTW interceptors are to be procured for deployment on Aegis cruisers and destroyers equipped with vertical launch systems.[65] The total program cost for the NTW system is not available because the final design has yet to be determined.

Finally, MEADS is a highly mobile 360° lower-tier defense designed to replace the HAWK air defense system for defending military forces in the field from air and tactical ballistic missile threats. A nominal deployment date of 2005 has been suggested, though this depends on funding commitments from the members of an international consortium (the United States, Germany, Italy, and possibly others).[66] As of this writing, there is a good chance the MEADS program will be canceled.

Several advanced technology demonstration programs exist for intercepting theater-range ballistic missiles in their boost phase. These concepts are based either on a high-speed airborne interceptor fired from fighter aircraft or unmanned aerial vehicles, a high-power airborne laser (ABL) carried aboard a Boeing 747-400F aircraft, or a space-based laser (SBL). The ABL has been selected as the Air Force's main boost-phase TMD program, with $1.3 billion funded for a prototype ABL to be deployed by 2002. The total procurement cost for seven airborne Lasers is projected to be $5.0 billion.[67] Space-based lasers are not examined in this paper because they are banned for national missile defense by the ABM Treaty and for theater missile defense by the Second Agreed Statement relating to the ABM Treaty signed on September 26, 1997.

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62 See Michael Dornheim, "Missile Defense Soon, But Will It Work?" *Aviation Week and Space Technology*, February 24, 1997, p. 39.

63 See John Pike, "Ballistic Missile Defense: Is the U.S. 'Rushing to Failure?'," op cit., pg. 11.

64 See Michael Dornheim, "'Theater Wide' Missile Defense Appealing, Controversial, Difficult," *Aviation Week and Space Technology*, March 3, 1997, pp. 62–63.

65 See "Navy Tactical Missile Defense," *World Missiles Briefing*, Teal Group Corporation, Fairfax, VA, 1996; and Michael Dornheim, "Missile Defense Soon, But Will It Work?" *Aviation Week and Space Technology*, February 24, 1977, p. 39.

66 See Joseph Anselmo, "MEADS Faces Tough Sell," *Aviation Week and Space Technology*, March 3, 1997, p. 57.

67 See Mark Hewish, "Scudkillers," *Jane's International Defence Review*, 1/1996, p. 31.

Notwithstanding the issue of countermeasures, there is relatively little debate about the need for lower-tier TMD systems such as PAC-3 or NAD to defend high-value targets. Perhaps the only debate is whether both are necessary. They have about the same coverage; however, PAC-3 is technically more mature and has the ability to defend inland targets. On the other hand, NAD can be deployed more rapidly to distant theaters and avoids the politically sensitive issue of prepositioning U.S. military equipment and personnel in the host nation before a war starts. Whether this difference justifies the added expense for two systems in an austere fiscal environment is doubtful. Of the two, PAC-3 clearly is the preferred system because of its ability to defend inland targets.

Debates over wide-area TMD systems, i.e., upper-tier and boost-phase systems, are more contentious. These systems may provide more effective theater missile defense; however, they also have a greater capability for intercepting strategic missiles and, hence, for upsetting strategic stability. Like PAC-3 and NAD, THAAD and NTW are also somewhat duplicative, although NTW coverage will be greater because of its higher flyout speed. Also, NTW does not require host-nation support. This analysis concentrates on THAAD-like defenses, as opposed to NTW, because THAAD is technically more mature and, hence, more information is available concerning its projected capabilities. Airborne boost-phase TMD systems will also be addressed.

How Much Upper-Tier TMD Is Enough?

The objective for theater missile defense used in this analysis is to protect allied cities and U.S. military forces from ballistic missiles armed with NBC warheads. Protecting allied cities is the more demanding objective. The performance criterion assumed for this analysis is a probability of 0.50 that no NBC warhead will land on any high-value target. The performance this requires for each TMD system is complicated because it depends on the number of layers in the overall TMD architecture. With the TMD systems currently under consideration, one can imagine three possible layers: a boost-phase layer, an upper-tier layer consisting of THAAD (or NTW), and a lower-tier layer consisting of PAC-3 (or NAD). THAAD (or NTW) may also operate in shoot-look-shoot mode, effectively providing two midcourse layers, though the footprint for shoot-look-shoot coverage shrinks. The boost-phase, upper-tier, and lower-tier layers can be treated as nearly statistically independent, provided separate surveillance and tracking sensors support each layer.[68]

PAC-3 (or NAD) is designed to defend high-priority targets (e.g., cities and large military facilities such as ports and airfields). However, the number of interceptors required to defend all important targets in a theater is too large for lower-tier defenses to meet the above defense performance criterion alone. Other TMD layers must be present. For the purpose of this analysis I assume that at least 25 high-value targets can be protected by a lower-tier

[68] A critical assumption underlying this analysis is that no common mode errors occur between the upper and lower tiers. If common mode errors exist between layers, they must occur less than 0.1 percent of the time for this analysis to remain valid.

defense. Therefore, the entire theater cannot be protected by a multi-layered TMD defense, only about 25 high-value targets (unless both boost-phase and midcourse layers exist).

To answer the question "How much upper-tier TMD is enough?" one must address the following two questions: how many upper-tier batteries (sites) are required to cover different theaters of interests and how many upper-tier interceptors must engage the incoming attack to meet the defense performance criterion? The number of TMD sites required depends on the TMD footprint, which is a complicated function of many factors.[69]

Figure 4 suggests that approximately 10 THAAD batteries are sufficient to cover South Korea and Japan against North Korean threats, assuming the defense operates in a barrage firing mode.[70] Shoot-look-shoot footprints would be considerably smaller. Although one THAAD footprint might cover South Korea, two footprints (i.e., batteries) are more reasonable given the density of cities and military facilities to be defended. The footprints covering Japan are smaller because they would be defending against higher-speed missiles, e.g., the North Korean No Dong or Taepo Dong missiles. A similar number of THAAD sites would be required to cover important areas within the Persian Gulf.

The coverage obtained with the NTW system is complicated by the fact that the NTW-defended footprint depends on the location of the NTW ships relative to the ballistic missile launch location. The most favorable scenario is coverage of Japan because NTW ships can be deployed between the threat (North Korea) and the territory being defended. In fact, NTW ships stationed in the middle of the Sea of Japan might be able to engage North Korean missiles in their ascent phase, thereby giving very large defended footprints behind the ship. In any case, approximately two to four NTW sites are required to defend all of Japan, depending on their location.[71] Defending South Korea requires an additional site. NTW coverage in the Persian Gulf would be more difficult due to the lack of accessible waters.

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[69] The most important factors are the interceptor flyout speed, the radar detection range (which is a function of the radar's power-aperture product, the target radar cross section, and the number of objects that must be engaged simultaneously), and the range (i.e., reentry speed) of the theater ballistic missile.

[70] The THAAD footprints covering South Korea are approximately 450 km in diameter and those covering Japan are approximately 350 km in diameter. These are based on estimates of THAAD performance made by the Congressional Budget Office. See *The Future of Theater Missile Defense*, Congressional Budget Office, Washington, DC, June 1994. They represent an upper bound on THAAD coverage because they are based only on the kinematics of a single THAAD intercept, i.e., the distance out to which a THAAD interceptor can fly to meet a single incoming warhead, given an estimate of the detection range for the THAAD ground-based radar. If multiple warheads attack targets located within a single defended area simultaneously, the defended footprint shrinks, and if the THAAD radar is queued by other sensors, the footprint increases—especially for long-range theater ballistic missiles. In addition, the probability with which a warhead will be destroyed is not uniform throughout this footprint, although for purposes of this analysis a uniform SSPK has been assumed.

[71] See Michael A. Dornheim, "'Theater Wide' Missile Defense: Appealing, Controversial, Difficult," *Aviation Week and Space Technology*, March 3, 1997, p. 62.

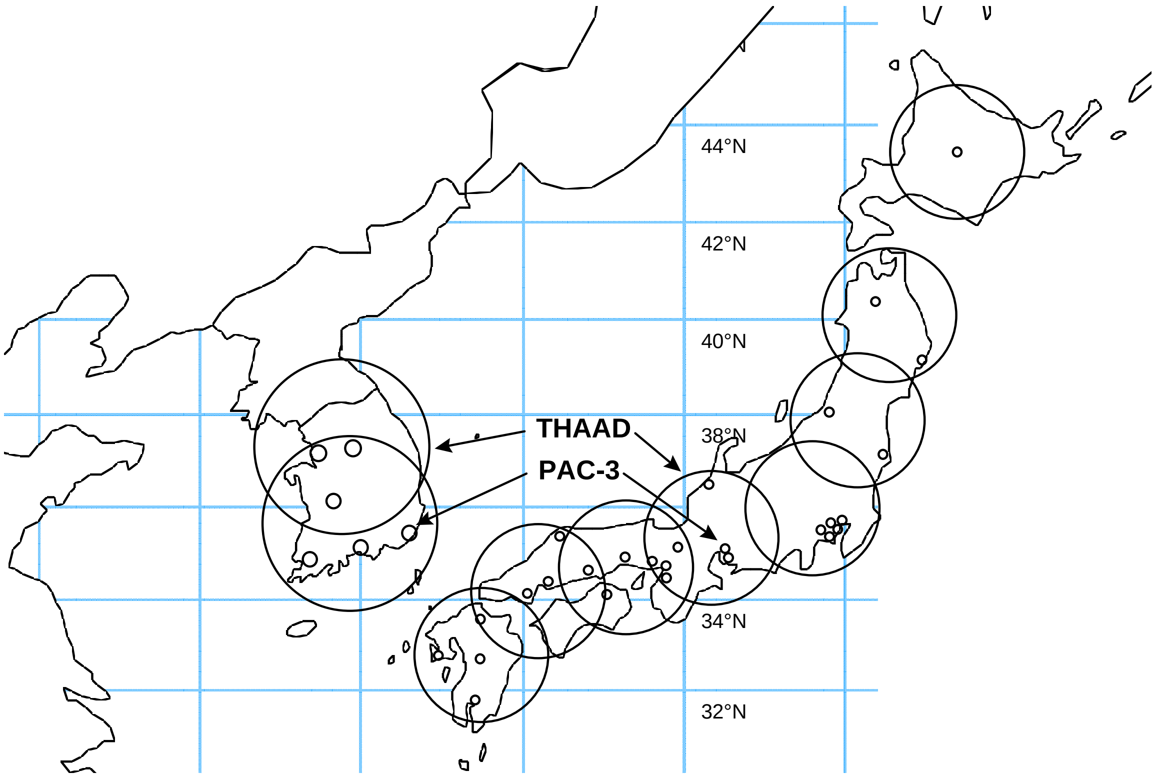

Fig. 4 - THAAD Coverage of Northeast Asia

The number of upper-tier (e.g., THAAD or NTW) interceptors that must engage the incoming attack is calculated assuming high-value targets are defended by an equally capable lower tier, i.e., THAAD and PAC-3 interceptors are assumed to have the same SSPK and both systems are assumed to have the same value for *P(track)*. In other words, the leakage rate for each layer is assumed to be the same. While this generally will not be the case, this assumption allows one to visualize how the required number of upper-tier interceptors varies with the overall technical performance of the defense. In addition, both layers are assumed to operate only in barrage mode (to achieve wide area coverage for THAAD and because insufficient time exists for PAC-3 to operate in anything but barrage mode). Therefore, this layered architecture provides a thin area defense over the entire theater with selected high-value targets protected by both upper and lower-tier defenses.

The required number of upper-tier interceptors, operating in a barrage mode, that must engage the incoming attack to ensure that no warheads leak through the upper and lower tiers with a probability of 0.5 is shown in Fig. 5 for an attack containing 100 warheads and no decoys, as a function of the SSPK and *P(track)* assumed for the upper and lower tiers. Figures 6 and 7 show similar plots for 200-warhead and 400-warhead threats, respectively, again assuming no decoys. The number of PAC-3 interceptors required in the lower tier has not been calculated. Generally, it will be far less than the number of upper-tier interceptors. Note that the minimum value for *P(track)* increases as the size of the threat increases. In

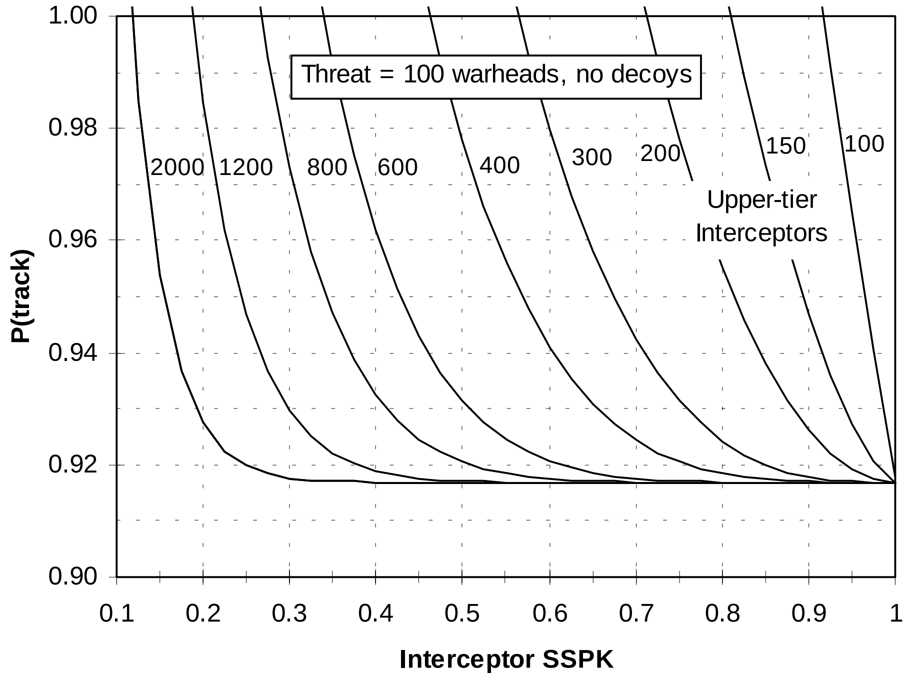

Fig. 5 - Upper-Tier Interceptors (Barrage Mode) For a 100-Warhead Attack

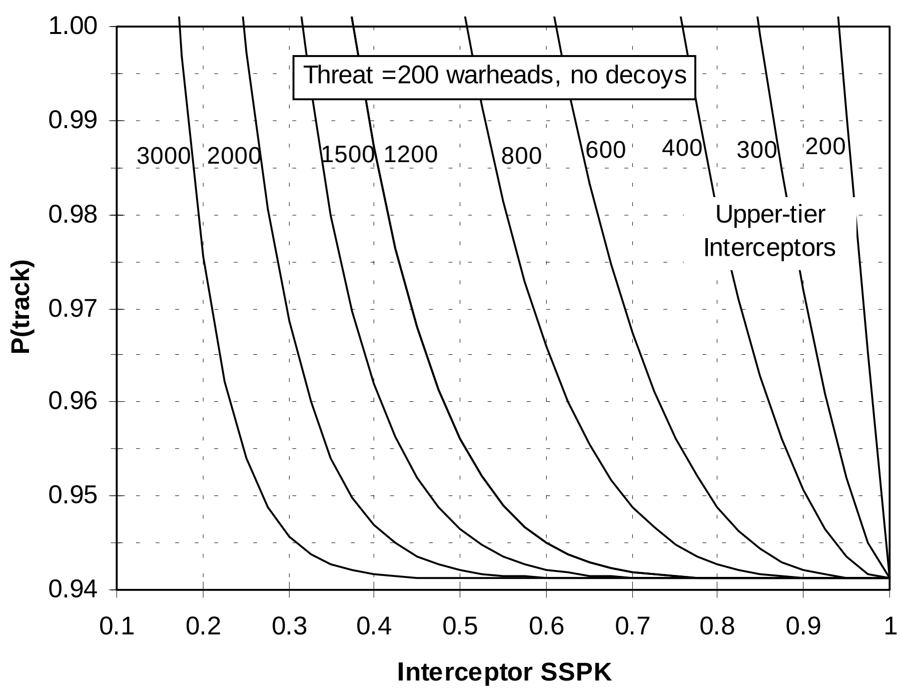

Fig. 6 - Upper-Tier Interceptors (Barrage Mode) For a 200-Warhead Attack

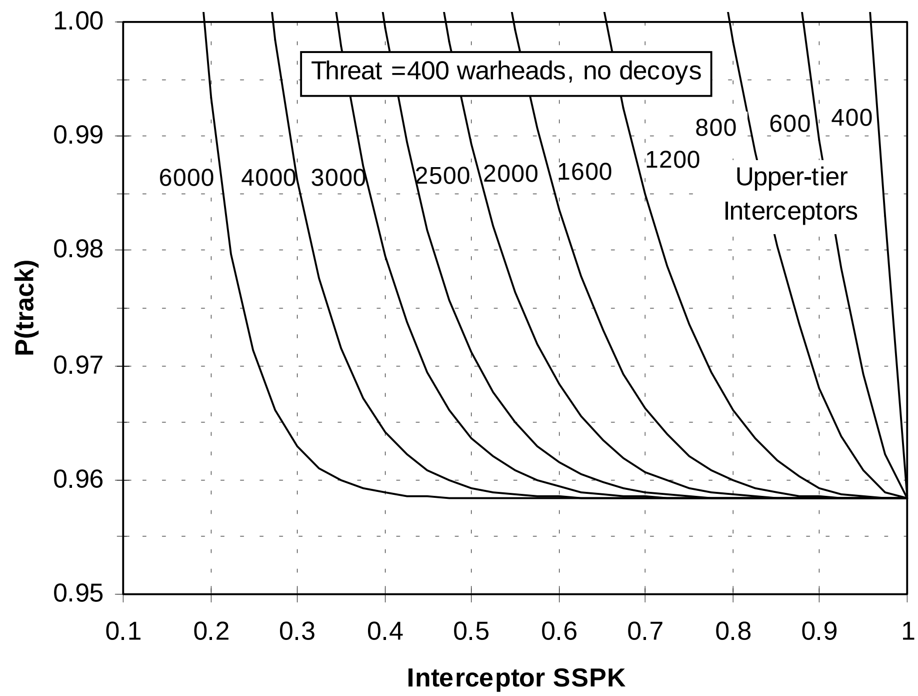

Fig. 7 - Upper-Tier Interceptors (Barrage Mode) For a 400-Warhead Attack

general, larger interceptor inventories can compensate for reduced technical performance, with the caveat that at some point so many interceptors must be fired at incoming targets that the defense battle space becomes saturated.

Therefore, if the current THAAD program (1,233 interceptors) is to meet the defense performance criterion for a 100, 200, or 400-warhead threat, this layered architecture would require a technical performance for both upper (i.e., THAAD) and lower (i.e., PAC-3) tiers with values of *P(track)* and interceptor SSPK to the right of the 1,200-interceptor contour lines in Figs. 5, 6, and 7, respectively, assuming the attack is spread uniformly over all defended sites. For example, for a 200-warhead threat, THAAD and PAC-3 interceptor SSPKs would have to be above 0.5, with independent detection and tracking probabilities above 0.96, for the current THAAD program to guarantee that none of the 200 warheads would land on high-priority targets in South Korea or Japan, assuming the entire THAAD interceptor stock is deployed to this theater in time of war. Again, for comparison, recall that TMD planners apparently hope for a THAAD SSPK as high as 0.80–0.85.[72]

However, an opponent will likely concentrate its attack in an effort to saturate one defended site, with the constraint that not all ballistic missiles can be launched in a single day. The maximum daily launch rate is limited by the number of available launchers. Although Scud-type missiles can be reloaded within several hours, few mobile launchers will

[72] See footnote 35.

be able to launch more than one missile per day because of the need to move and hide immediately after launch to avoid U.S. air attacks.[73] Fixed ballistic missile launch sites will be destroyed very rapidly in a conflict or war involving the United States. Historically, countries have deployed between 4 to 15 missiles per mobile launcher (Iraq had about 13 missiles per launcher), suggesting that at most 7–25 percent of the arsenal can be launched in a single day.[74] For example, during the 1991 Gulf War no more than 14 Al Hussayn missiles were fired in a single day (80 percent were launched at night), which corresponds to 3.5 percent of Iraq's arsenal prior to the war.[75] Therefore, each defended site must have enough interceptors to handle this fraction of the total arsenal, under the assumption that subsequent attacks can be handled by replenishing interceptors at the site(s) being exhausted within less than 24 hours from storage sites in theater.

For example, if 10 THAAD sites are required to cover South Korea and Japan, each site can handle attacks of up to 10 percent of the total ballistic missile arsenal in a single day. The total number of interceptors that must be deployed to the theater to guarantee that no single site can be saturated is equal to 1.9 times the number of interceptors given in Figs. 5–7.[76] In other words, a THAAD program with approximately 1,200 interceptors must have a technical effectiveness to the right of 630-interceptor contour lines in Figs. 5–7 to meet the defense performance criterion if the attack is concentrated against targets located in a single defended footprint because only 630 interceptors will be able to engage the attack in this scenario. If North Korea can launch more than 10 percent of its arsenal against a single defended area in one day, then the number of interceptors that must be deployed at each site increases. For example, if 20 percent of the arsenal can be launched in a single day, twice the number of THAAD interceptors must be deployed at each site and 2.8 times the total number of interceptors obtained from Figs. 5–7 must be deployed to the theater to guarantee that no single site can be saturated.[77] Figs. 5–7 also allow one to assess the impact

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[73] An estimate of 2–4 hours for the Scud reload time is given by Thomas Cochran, William Arkin, Robert Norris, and Jeffrey Sands, *Nuclear Weapons Databook, Vol. IV: Soviet Nuclear Weapons*, Natural Resources Defense Council, 1989, p. 221.

[74] For example, Russia deployed four missiles with each Scud B mobile launcher. See *Jane's Strategic Weapons Systems*, September 1995, Issue 19. On the other hand, East Germany apparently deployed around 5–6 Scud B missiles for each launcher. For Iraq the ratio was closer to 13 Scud B or Al Hussayn missiles per mobile launcher. See David Isby, *Jane's Intelligence Review*, Vol. 7(3), March 1995, pp. 115–117.

[75] This is around half the maximum daily launch rate Iraq could have attained. One should also note that the average daily Scud launch rate dropped threefold (from 4.7 to 1.5 launches per day) after U.S. Scud-hunting operations began. See *The Gulf War Air Power Survey, Summary Report*, Vol. I, Part II (Washington, DC: U.S. Government Printing Office, 1993), pp. 84–87.

[76] Since the number of interceptors derived in Figs 5–7 are spread throughout S sites, the fraction of the ballistic missile arsenal that each site can defend against is $1/S$. In general, $2-1/S$ times the number of interceptors required to engage the attack must be deployed to the theater to guarantee that no single site can be saturated for a defense containing S defended sites.

[77] The general equation for the total number of interceptors that must be deployed to the theater is $I(S+M-1)/M$ where I is the total number of interceptors that must engage the attack from Figs 5–7, S is the number of

of countermeasures that reduce warhead detection and tracking capabilities or interceptor SSPKs; that is, assuming one can determine by how much these parameters might be degraded (which is difficult because it depends on the technical details of the countermeasure and defensive counter-countermeasures).

Finally, if the attack contains decoys that cannot be discriminated by the defense, the number of interceptors required to meet the defense performance criterion can be obtained by multiplying the number of interceptors along any given contour line in Figs. 5–7 by the ratio of the number of apparent warheads to the number of real warheads in the attack.[78] The attack sizes in Figs. 5–7 correspond to the number of real warheads. For example, if the attack contains two effective decoys for each warhead, then a 1,200 THAAD interceptor deployment must have a technical performance to the right of the 400-interceptor contour lines in Figs. 5–7 to meet the defense performance criterion, assuming the attack is spread uniformly across all defended areas and that no more than 10 percent of the opponent's arsenal can be fired in a single day. That is, for an attack containing 100 real warheads and 200 effective decoys, the upper and lower tiers must have a technical performance to the right of the 400-interceptor contour line in Fig. 5, e.g., detection and tracking probabilities above 0.94 and SSPKs above 0.6, in order for the defense to completely block all 100 real warheads from among 300 apparent warheads with a probability of 0.5. If the attack is concentrated against targets located within a single THAAD defended footprint, then the technical performance would have to be approximately to the right of the 200-interceptor contours in Figs. 5 and 6—demonstrating that effective decoys and saturation tactics, to the extent they can be implemented, increase appreciably the technical performance required for the defense.

Using the best scenario for the NTW system, i.e., the defense of Japan, one can use Figs. 5–7 to determine the technical performance required for a 650-interceptor NTW system to meet the same defense performance criterion—again, assuming that high-priority targets are defended by a lower-tier defense and that both layers have the same leakage rate. For example, if three NTW sites are required to defend South Korea and Japan and all 650 interceptors are deployed at these sites, then the NTW system would have to have a technical performance to the right of 650-interceptor contour lines in Figs. 5–7 to meet the performance criterion for 100, 200, and 400-warhead threats, respectively. If the offense concentrates its attack against targets located within a single NTW footprint but can launch no more than 25 percent of its arsenal in a single day, then the technical performance required for a 650-interceptor NTW system would have to be approximately to the right of 430-interceptor contour lines in Figs. 5–7. Note that the NTW system is more robust to saturation tactics than THAAD because the NTW system has a larger defended footprint and each Aegis cruiser can carry more NTW interceptors than each THAAD battery. However, in general, the NTW system will require higher technical performance to meet a

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TMD sites required for complete coverage, and *M* is the number of theater ballistic missiles per launcher in the arsenal.

[78] Again, to be precise this is true only for barrage firing doctrines.

given threat because of the smaller interceptor inventory (650 compared with approximately 1,200 for THAAD), assuming all the interceptors are deployed to a given theater of interest.

How Much Airborne Boost-Phase TMD Is Enough?

Although technically more challenging, boost-phase theater missile defense is attractive because missile boosters are relatively easy to detect and track by radar and infrared sensors, boosters are easier to destroy than warheads, kill assessment—a non-trivial task for midcourse defense—is relatively easy because thrust termination or catastrophic collapse of the booster can be verified using accurate track data, and the entire payload (warheads and penetration aids) can be destroyed in a single shot. Moreover, if intercepted several seconds before booster burnout, the debris will fall short of the target area, potentially avoiding collateral damage to friendly territory. Finally, booster decoys are difficult to build.[79] In short, boost-phase theater missile defense has similar advantages to the boost-phase strategic missile defense that animated President Reagan's Strategic Defense Initiative. However, unlike boost-phase strategic defense, boost-phase theater missile defense can be conducted from aircraft and hence does not require space-based weapons, at least for small states, because aircraft can get close enough to theater missiles during their boost phase. Only airborne boost-phase TMD concepts will be discussed in this paper.

Another advantage of boost-phase TMD, at least against small states, is that the defense only needs to cover the opponent's territory as opposed to all friendly or allied territory within ballistic missile range. Intelligence information can be used to further localize possible launch areas.[80] Consequently, airborne boost-phase TMD systems may be effective against small states such as North Korea but would be largely ineffective against large states such as Russia and China, or against any state that can deploy ballistic missiles on submarines. Consequently, such defenses pose relatively little threat to the strategic forces of any of the five major nuclear powers.

Airborne Interceptor

The airborne interceptor is a high-speed rocket launched either from a fighter or unmanned aerial vehicle (UAV) that loiters over or near enemy territory. It employs a kinetic-kill vehicle that homes on the booster's infrared signature. ABIs would probably receive booster track information from an airborne radar and/or infrared sensor platform, although track

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[79] Small, cheap sounding rockets with the same thrust-to-mass ratio as the theater ballistic missile being decoyed and with corner reflectors to reproduce the theater ballistic missile radar cross section could be built in large numbers and fired simultaneously with each theater ballistic missile, making it difficult to distinguish the booster by radar alone. Infrared sensors can distinguish the booster from such decoys. However, this implies that decoy discrimination would be delayed until the booster rises above any clouds that might be present—a time delay on the order of 35–40 seconds.

[80] For example, during the 1991 Gulf War, mobile Scud launches were confined to less than one-quarter of Iraq's territory. See Barry Watts and Thomas Keaney, "Effects and Effectiveness," *Gulf War Air Power Survey*, Vol. II, Part II (Washington, DC: U.S. Government Printing Office, 1993), p. 400.

information could conceivably come from space-based sensors or from sensors aboard the launch platform itself (e.g., the F-15 fire-control radar or an infrared search and track system).

The defended footprint for ABIs depends on the interceptor flyout speed, the burn time for the theater ballistic missile booster, and the time delay between the launch of the ballistic missile and the ABI. ABIs based on current rocket motors can probably achieve maximum speeds around 3 km/sec, although 6–7 km/sec ABIs should be technically feasible for 500 kg-class rockets assuming a 35 kg kinetic-kill vehicle. Theater ballistic missile boost times are typically between 60–120 seconds, depending on the range and design of the missile. Finally, the time available for ABI flyout is equal to the theater ballistic missile boost duration minus the time delay between the theater ballistic missile and ABI launches. This time delay occurs because it takes time to detect and accurately track ballistic missiles. Establishing an accurate track could occur 20–30 seconds after ballistic missile launch, though 45 seconds is probably more reasonable if infrared sensors are required to positively identify boosters after they climb above any clouds that might be present (i.e., the time it takes to reach an altitude of about 10 km since clouds occur less frequently above this height). Typical intercept ranges for near-term (i.e., 3 km/sec) ABI systems are between approximately 50 km and 150 km for theater ballistic missiles with ranges between 300 km and 3,000 km. At the high end, 6 km/sec ABIs can have intercept ranges between approximately 100 km and 300 km for missiles with ranges between 300 km and 3,000 km.[81]

Figure 8 illustrates the ABI coverage of North Korea using 4 km/sec ABIs with 45-second launch delays against Scud B, Scud C, and No Dong–like missiles with boost times of 75, 84, and 91 seconds, respectively.[82] Approximately four or five ABI orbits should be sufficient to cover most of North Korea. Fewer would be required if significant launch area localization can be achieved. If the Taepo Dong-1 missile is deployed by North Korea, with an estimated range of over 2,000 km and a burn time probably over 100 seconds, then a 4 km/sec ABI should be able to intercept this missile from approximately 150–200 km away (assuming a 45-second launch delay), implying that two or three ABI footprints would cover North Korea and that the Taepo Dong might be vulnerable to ABIs orbiting outside North Korean airspace. Four to five ABI orbits would also provide reasonable coverage of Iraq for different range theater ballistic missiles, although it is insufficient for a large state such as Iran unless very high-speed interceptors are available, reaction times can be reduced below 45 seconds, or significant area limitation can be achieved.

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[81] See Dean A. Wilkening, *Airborne Boost-Phase Theater Missile Defense*, CISAC Working Paper, Center for International Security and Cooperation, Stanford University, Stanford, CA, to be published.

[82] If the No Dong has a burn time as short as 70 seconds, as suggested in the literature, then the No Dong footprint dimensions would shrink to approximately the size of the Scud B footprint, implying that three times the number of orbits would be required to cover North Korea. See David Wright and Timur Kadyshev in "An Analysis of the North Korean Nodong Missile," *Science and Global Security*, Vol. 4, 1994, pp. 129–160.

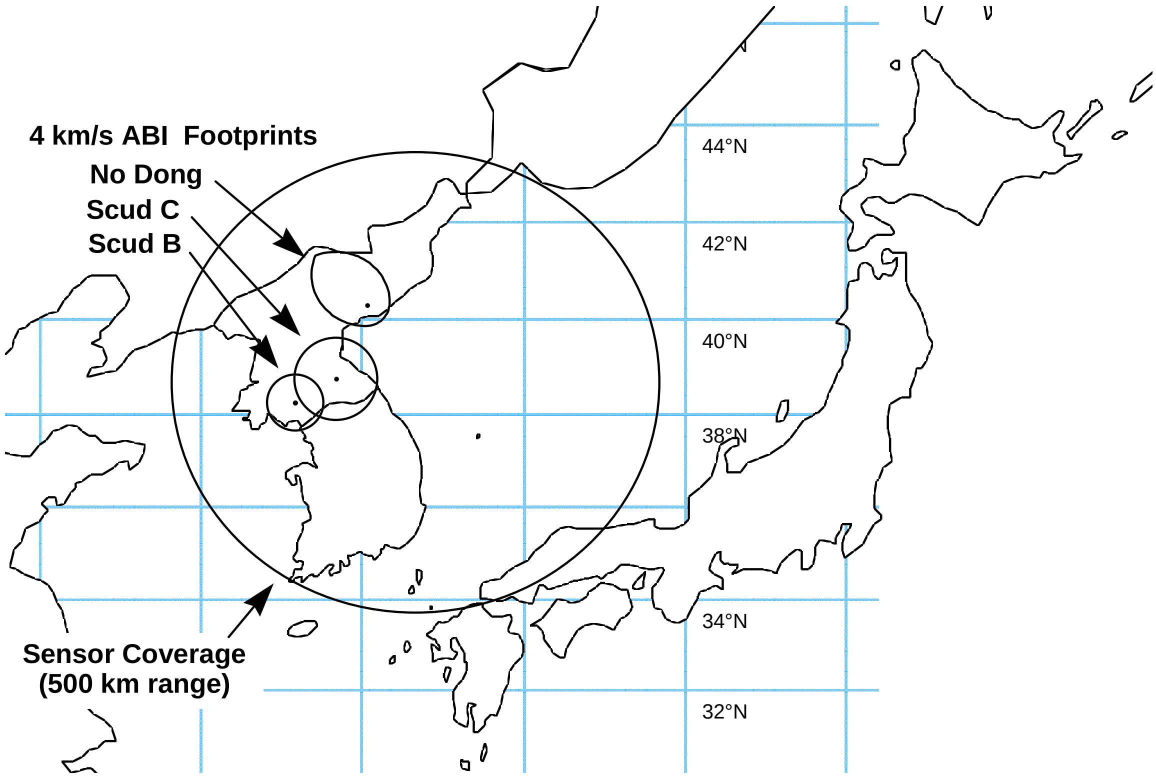

Fig. 8 - ABI Coverage of North Korea

The number of ABIs required to meet a given defense performance criterion can be determined from calculations similar to those for upper-tier TMD defenses, except that ABI systems cannot operate in shoot-look-shoot mode due to insufficient time. The number of ABIs that must be on station in any given footprint is calculated by multiplying the number of ABIs that must be launched at each ballistic missile to meet the defense performance criterion by the maximum number of missiles that can be launched from within the ABI-defended footprint during the time it takes to replace ABI platforms that have exhausted their interceptors (approximately one hour). This is assumed to be the same as the maximum daily launch rate discussed above, assuming all mobile launchers can concentrate in a single ABI footprint and that they can fire their missiles within one hour.[83]

For example, approximately 540 ABIs are required to defeat 200 missiles with a probability of 0.5 (i.e., 2.7 ABIs per missile), assuming an ABI SSPK of 0.7, a missile detection and tracking probability of 0.98, and that the subsequent layer has the same leakage rate for warheads as the boost-phase layer has for missiles (see Fig. 6). Therefore, 54 ABIs must be on station within each footprint assuming no more than 20 missiles can be launched within one hour. To find the number of ABI launch platforms one simply divides

83 These are optimistic assumptions for the offense because concentrating mobile launchers in this manner may make them vulnerable to air attack, not to mention that if these concentrations are detected in time, ABI aircraft can be concentrated against them.

by the carrying capacity of each platform. Typically, four to eight ABIs can be carried aboard each fighter aircraft and perhaps as many as four ABIs on a large UAV such as the Global Hawk. Therefore, between 7–14 F-15s, depending on the loading, or 14 Global Hawk UAVs would have to be on station within each ABI footprint for the duration of the ballistic missile threat. It takes about four to five F-15s in the inventory or about three Global Hawk UAVs to maintain one airborne 24 hours a day.[84] Hence, the total force structure required to defend against North Korean Scud B, Scud C, No Dong, and Taepo Dong attacks containing up to 200 missiles would be approximately 175–350 F-15s or 210 Global Hawk UAVs, assuming five orbits. Consequently, if F-15s are used as ABI launch platforms, the number devoted to the boost-phase TMD mission would have to be between 50 to 100 percent of that devoted to the theater air defense mission.[85] This calculation, of course, is only representative of typical ABI force structures. Estimates will vary depending on the exact details of the ABI system, its technical performance, and the maximum salvo launch threat.

Boost-phase TMD is the only active defense capable of handling fractionated CBW threats, as well as other sophisticated penetration aids that may defeat upper or lower-tier TMD systems. To calculate the effectiveness of an ABI defense against fractionated CBW payloads one must note that subsequent TMD layers likely will be ineffective. The number of ABIs required to ensure a 0.5 probability that no missile leaks through a single boost-phase layer is shown in Figure 9, for different values of the ABI SSPK and a missile detection and tracking probability of 0.98. For example, if 54 ABIs each with an SSPK of 0.7 are on station in each footprint to meet the former defense criterion, this force could guarantee (with a probability of 0.5) that no CBW submunitions penetrate the defense for attacks containing up to 17 missiles launched against a single ABI orbit. For larger attacks, some missiles will penetrate the boost-phase layer, presenting subsequent TMD layers with a large number of CBW submunitions. Therefore, while the ABI may be an effective defense against responsive threats, it cannot provide a near-perfect defense by itself.

The most serious operational limitation associated with ABI systems is that ABI launch platforms and, for large states, airborne sensor platforms cannot provide adequate coverage from orbits outside hostile air space. This presents a problem during the crisis phase of a conflict when theater ballistic missile threats may have their greatest political leverage because U.S. leaders may not allow ABI platforms to penetrate the opponent's airspace until the war has started. Violating a nation's airspace with armed aircraft is an act of war and,

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84 Fighters can maintain combat air patrols for about eight hours. Therefore, three fighters are required to provide 24-hour coverage. An additional one or two aircraft are required as spares in case serious maintenance problems ground one of these planes. The Global Hawk UAV is supposed to have an on-station time between 4 to 25 hours, depending on the payload. A nominal on-station time of 12 hours implies that 3 UAVs would be required to maintain one on orbit for 24 hours.

85 Currently, the U.S. Air Force has 627 F-15s of all types in the active inventory, about 400 of which are used for theater air defense (i.e., F-15C/Ds). See USAF Almanac 1996, *Air Force Magazine*, May 1996, pp. 56–58.

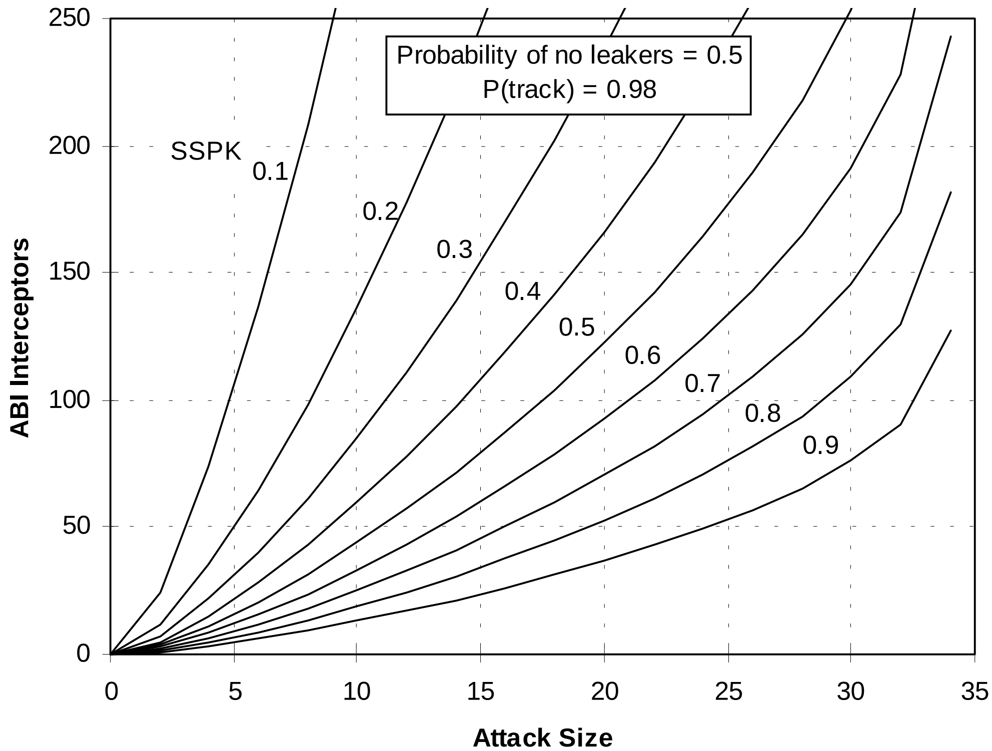

Fig. 9 - ABIs Required to Defeat Fractionated CBW Payloads

hence, would be a politically provocative step—not to mention the risk to the pilot. However, ABI aircraft should be able to penetrate enemy airspace within the first minutes of the war.[86] Note that the first Iraqi Scud missiles launched in the 1991 Gulf War came 24 hours after the air war began, though this may not be typical of future conflicts.[87] On the other hand, if the opponent withholds his weapons of mass destruction to deter threats to the survival of his state or regime, as is believed was the case with Saddam Hussein during the 1991 Gulf War, then NBC-armed ballistic missile threats against cities would come late in the war.

The investment cost for ABI systems is largely determined by the cost of the ABI launch platforms (assuming new platforms are acquired) and sensor platforms (e.g., airborne radars).

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[86] In Operation Desert Storm, Iraq's integrated air defense system was paralyzed within the first few hours of the war. However, it took weeks to suppress most of the radar-guided SAMs that posed the largest threat to aircraft flying above 20,000 ft. Even so, only nine fixed-wing aircraft were lost during the first week of the war. Fourteen were lost during the entire war, and only four of these were due to radar-guided SAMs. See the *Gulf War Air Power Survey, Statistical Compendium and Chronology*, Vol. V, Part II (Washington, DC: U.S. Government Printing Office, 1993), pp. 642–647.

[87] The Department of Defense, *Gulf War Air Power Survey, Statistical Compendium and Chronology*, Vol. V, Part II (Washington, DC: U.S. Government Printing Office, 1993), p. 160.

The ABI missiles are relatively inexpensive (on the order of $2 million each).[88] Assuming each airborne radar costs around $400 million, the investment cost for an ABI system with 1,000 ABIs—enough to cope with threats of up to 200 missiles armed with unitary warheads, assuming ABI SSPKs above 0.5 and missile detection and tracking probabilities above 0.97—and eight airborne radar platforms would be around $5 billion, assuming existing F-15 platforms are used. If new F-15 aircraft are procured, the additional procurement cost would be around $6–12 billion for a fleet of 175–350 aircraft, bringing the total ABI procurement cost to around $11–17 billion.[89] Recall that the total development and procurement cost for THAAD is projected to be around $18 billion. Procurement cost estimates for UAV-based ABI systems are less reliable due to the immaturity of these systems. Nevertheless, assuming a modified Global Hawk UAV can carry four ABIs with coverage comparable to that shown in Fig. 8 and that it can remain on station for approximately 12 hours, one arrives at an estimate of $4.6 billion for 210 UAVs and 1,000 ABIs to fill five orbits.[90] If airborne radar platforms are also required because sensors aboard the UAV cannot provide sufficient ballistic missile detection and tracking, an additional $3.2 billion would be required to procure eight airborne radars, increasing the total system cost to around $7.5 billion. These preliminary cost estimates suggest that UAV launch platforms may be the most cost-effective ABI option.

Airborne Laser

The current ABL concept is based on a 3 MW chemical oxygen-iodine laser carried aboard a Boeing 747-400F freight aircraft. The maximum ABL lethal range, i.e., the range if the ABL dwells on the missile from the time it becomes visible until the boost phase is finished, is reported to be on the order of 400–500 km.[91] Enough chemicals for the laser will be carried aboard each plane for 20–40 nominal shots, where the actual shot capacity varies depending on the engagement range and the hardness of the missile booster. The current ABL program envisions deploying seven ABL aircraft by the year 2008 (the first ABL would be available around 2006). This force should be able to support two ABL orbits 24 hours a day.

Lasers destroy boosters by depositing sufficient energy to weaken the booster casing, thereby either causing the booster to vent rapidly if a hole is punched in the booster's side or

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[88] This estimate assumes each ABI is twice the cost of an AAMRAM, the most advanced long-range air-to-air missile in the U.S. inventory, which cost about $1 million apiece.

[89] F-15 procurement costs are estimated to be $35 million per aircraft for the McDonnell Douglas F-15E. See *Jane's All The World's Aircraft, 1992–93*, Jane's Data Group Limited, Surrey, UK, 1992, p. 408.

[90] This is based on an estimate of $10 million for each Global Hawk UAV, $2 million for each ABI, and $485 million in fixed costs for ground stations and other squadron equipment. See Pamela Hess, "BMDO Sees Potential in Using UAVs for Boost-Phase Intercept Mission," *Inside Missile Defense*, Vol. 3, No. 18, September 10, 1997, p. 1.

[91] See Mark Hewish, "Scudkillers: Tough choices for boost-phase intercept," *Jane's International Defence Review*, January 1996, pp. 28–34.

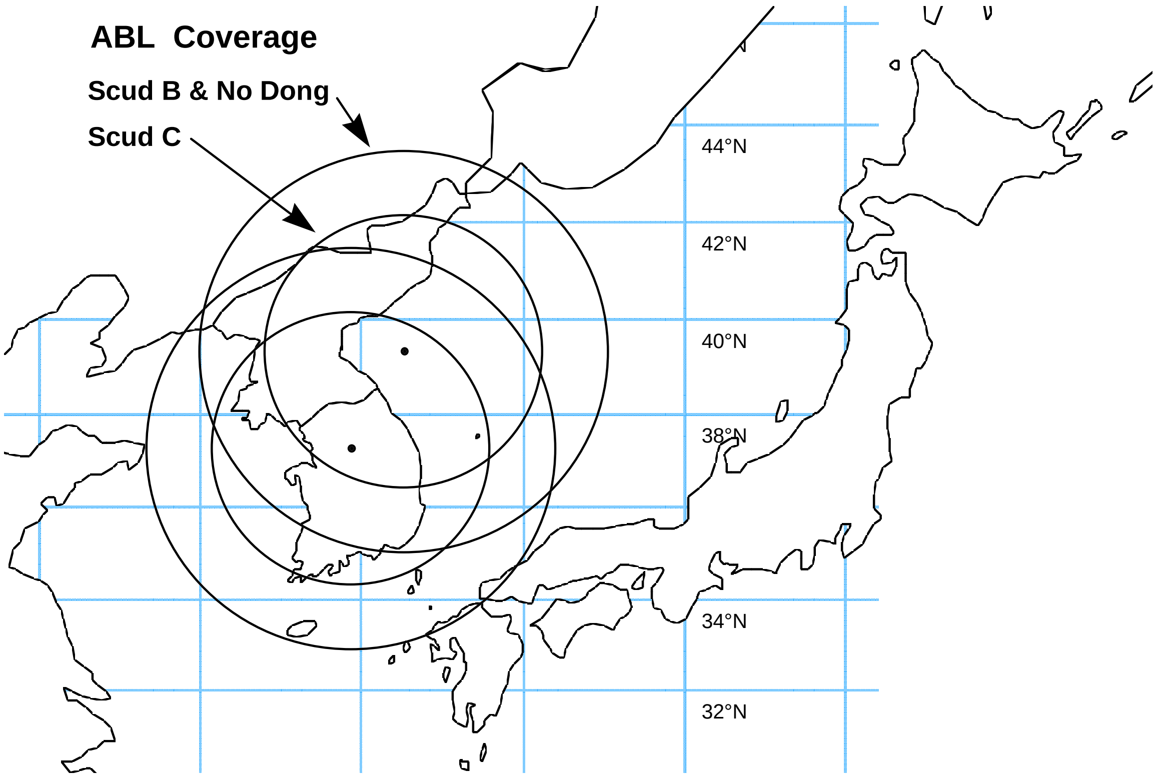

Fig. 10 - ABL Coverage of North Korea

causing the booster to collapse catastrophically under the axial load from the missile's acceleration. The dwell time required for effective destruction is a function of the booster casing material, the range to the target, the laser power, and the size of the optics. Since the ABL dwells on each missile booster until destruction occurs, its effectiveness cannot be modeled by a simple SSPK independent of range. In theory, the SSPK should be close to unity if the target is within the ABL lethal range and close to zero if it is beyond this range. Therefore, answering the question "How many ABL platforms are enough?" essentially reduces to answering the question of the lethal range of the ABL.

One analysis concludes that the maximum lethal range for the ABL should be approximately 320 km against Scud B and No Dong missiles and approximately 470 km against the Scud C (or Al Hussayn) missile.[92] Figure 10 illustrates the coverage of North Korea that should be possible assuming these lethal ranges. As one can see, a single orbit 90 km outside North Korean airspace (to avoid air defenses) covers almost the entire state, though two or more would be required for Iraq and several more would be required to cover

[92] These are the range estimates for punching a simple hole in the booster's side, thereby causing booster venting. Estimates for the maximum range for a more catastrophic booster failure are shorter, namely, 240 km, 320 km, and 185 km for the Scud B, Scud C (or Al Hussayn), and No Dong missiles, respectively. See Geoffrey Forden, "The Airborne Laser," *IEEE Spectrum,* September 1997, pp. 40–49; and Geoffrey Forden, *The Airborne Laser: Shooting Down What's Going Up*, CISAC Working Paper, Center for International Security and Arms Control, Stanford University, September 1997.

Iran. One should note that for large states (e.g., Iran) the ABL cannot cover all possible launch locations from orbits outside the opponent's airspace, implying that the ABL would have to penetrate enemy airspace after its air defenses have been suppressed—a very risky tactic with such a large, high-value platform. Finally, if the ABL must contend with several missiles simultaneously, the maximum lethal range is reduced because the ABL must split its time between two or more targets. Hence, seven ABL aircraft supporting two ABL orbits provides an adequate initial boost-phase theater missile defense. However, this assessment could change dramatically if the lethal ranges for the ABL cited here drop by more than 20 percent; for example, due to enemy countermeasures such as coating the booster to harden it against laser radiation, at some expense in missile range, or rotating the booster in flight (which requires a sophisticated missile guidance system).

The total acquisition cost for the ABL program has been estimated at $5 billion and the total life-cycle cost over 20 years at $11 billion.[93] Hence, the ABL, if it works, represents the least expensive boost-phase TMD option, assuming new fighter aircraft must be procured for the fighter-based ABI system and that airborne radars must be deployed to complement the sensors planned for the Global Hawk UAV ABI launch platform.

Concluding Observations

This analysis, in some respects, supports the Clinton administration's approach to ballistic missile defense—to conduct research and development on a thin national missile defense with the option of deploying a system with up to 100 interceptors if, or when, credible intercontinental ballistic missile threats appear on the horizon, and to deploy between 1,000 to 2,000 upper and lower-tier TMD interceptors in a layered theater missile defense—but only if a high level of technical performance can be achieved by the defense.

There is no immediate need to deploy a thin national missile defense because the likelihood of accidental, unauthorized, or inadvertent Russian or Chinese ballistic missile attacks is assessed to be low and, although developing states may be able to deploy ICBMs within 5–10 years, the United States has other options for dealing with these potential threats, namely, deterring their use by threatening devastating retaliation, and conventional counterforce options for attacking fixed ICBM or space-launch sites if it is believed that deterrence might fail. National missile defense might provide useful insurance against the possibility of an accidental or unauthorized attack, or against the failure of deterrence and conventional counterforce, but one must assess the opportunity costs of spending money on such insurance as opposed to other pressing military needs. Finally, it is prudent to allow more time for U.S. missile defense technology to mature, especially in light of the poor test

93 See Michael Ruane, "U.S. looks to lasers to destroy missiles," *Philadelphia Inquirer*, April 8, 1997, p. 1; and George Seffers, "Some USAF Officials Predict Limits on Airborne laser Role," *Defense News*, November 18–24, 1996, p. 8.

performance for hit-to-kill interceptors to date, before deploying a thin national missile defense.

When the need for a thin national missile defense becomes apparent, 100 NMD interceptors deployed at one or two sites around the continental United States should provide adequate protection against threats containing up to 10 apparent warheads provided NMD interceptors can achieve SSPKs above 0.35 and warhead detection and tracking probabilities above 0.99. If the threat contains more than 20 apparent warheads, NMD systems will either require in excess of 100 interceptors, NMD interceptor SSPKs above 0.65 and detection and tracking probabilities above 0.994, or effective decoy discrimination. Recall that one cannot determine the expected size of accidental or unauthorized attacks with much precision in any case. Finally, the ABM Treaty will either have to be modified or abrogated to allow such defenses. Whether this will happen in the near future is an open question.

Theater-range ballistic missiles pose the greatest near-term missile threat. Hence, theater missile defense should be, and has been, the highest priority among U.S. ballistic missile defense programs. The most challenging TMD mission is to protect allied cities to help prevent allied leaders from being coerced by regional opponents in possession of NBC-armed ballistic missiles. In this regard, layered theater missile defenses are attractive because they offer the prospect of low leakage. In particular, the current THAAD program (with an expected deployment of approximately 1,200 interceptors) will have to achieve a technical performance with detection and tracking probabilities in the range 0.96–0.98 and interceptor SSPKs in the range 0.4–0.65 to deal with threats between 100–200 apparent warheads. Similarly, the current NTW program (with 650 interceptors) will require the same detection and tracking probability, but with interceptor SSPKs in the range of 0.55-0.80 to deal with the same size of threat. Finally, to make the layered defense work, high priority targets, e.g., cities, must be protected by a lower-tier defense, e.g., PAC-3, with essentially the same level of technical performance. Whether such high detection and tracking probabilities and interceptor SSPKs can be achieved in the presence of enemy countermeasures is far from obvious. Hence, this should be the focus of intense engineering and field testing in the years ahead.

Finally, the main limitation of upper and lower-tier theater missile defenses is their potential vulnerability to countermeasures that probably can be deployed by modestly sophisticated adversaries. However, there are relatively few effective countermeasures to airborne boost-phase TMD systems. This is especially true for the ABI, whereas the ABL may be vulnerable to booster hardening and booster rotation. While the ABL has been chosen as the main U.S. airborne boost-phase TMD option, research on ABI systems should receive increased funding to hedge against the possibility that technical problems will delay ABL deployment. In short, given their attractiveness, research and development on effective airborne boost-phase TMD systems should receive higher priority, especially in light of the fact that these systems pose very little threat to the strategic nuclear forces of any of the five major nuclear powers.