BALLISTIC MISSILE DEFENSE: CAPABILITIES AND CONSTRAINTS

ALWYN YOUNG

Numerous proposals for Ballistic Missile Defense (BMD) are receiving serious policy consideration, both in and out of government. In this article Alwyn Young examines such proposals and the advantages and disadvantages of different BMD systems in terms of the possible missions they are meant to perform. While not trying to offer judgments on the overall desirability of BMD from a strategic or arms control perspective, Young does review the current status of BMD technology and he focuses on the critical conditions that will determine BMD mission-performance capabilities.

INTRODUCTION

Analyses of the potential capabilities of strategic Ballistic Missile Defense (BMD) systems frequently evolve from each analyst's preconceptions as to what type of strategic balance is desirable. Deterrence theorists, for example, usually dismiss BMD as being cost-inefficient. These theorists present scenarios in which the attacking power can easily and cheaply saturate the BMD system. It is argued that BMD could never achieve favorable "cost-exchange" ratios — the amount of defensive dollars which may be required to offset each additional offensive dollar. This type of analysis derives from the deterrence theorists' assumptions about the supremacy of the nuclear offensive. In contrast, experts who would rather replace "Mutual Assured Destruction" with "Mutual Assured Protection" and those who believe in nuclear war fighting present scenarios in which BMD systems achieve superior cost-exchange ratios and provide an almost foolproof defense. The analyses and scenarios presented are prejudiced by their desire to rid the world of mutual vulnerability (i.e., assured countervalue strikes) and redefine the nuclear balance in defensive or counterforce terms. Proponents of both these viewpoints, therefore, bring significant biases to the debate over the feasibility of strategic BMD systems.

To clarify the issue at hand, an analogy would be useful. Under appropriate conditions, a tank is always superior to antitank defenses. Even though antitank weapons are considerably cheaper than tanks, in a fluid battlefield environment tanks can bypass static antitank positions and thereby reduce

Alwyn Young is a candidate for the MALD degree at the Fletcher School of Law and Diplomacy.

their effectiveness. Under a different set of battlefield conditions (e.g., when antitank weapons are in fortified positions, can engage tanks at long ranges, and have both frontal and flank fire on the attacking tanks), antitank weapons can inflict horrendous "cost-effective" losses on unsupported enemy tank forces. To base one's analysis of the utility of tank or antitank forces purely on either of these scenarios would be ludicrous. Rather, an analysis should attempt to identify under what set of conditions tanks are superior (in cost-exchange terms) to antitank defenses and under what conditions they are not. This type of analysis has led to the development of tanks with different specifications for different battlefield roles, the use of various supporting weapon systems for specific tank missions, and has guided the overall development of tactics and strategy of land warfare.

The purpose of this article is to present a tactician's and strategist's approach to the technical problems of Ballistic Missile Defense (BMD). Past, current and near-future capabilities of BMD systems will be analyzed in terms of possible BMD missions and the overall advantages and disadvantages of different BMD systems. The aim is both to provide an overview of BMD systems and to derive the critical conditions affecting BMD cost-exchange ratios and mission performance capabilities. This article does not analyze the strategic and arms control implications of BMD. This is not to denigrate the *central importance* of these issues. This article is not intended to supplant the debates on the strategic and arms control desirability of BMD. Rather, its purpose is to help inform these debates on the current state of BMD technology and on the conditions and variables that will determine the capabilities of strategic BMD systems in the next 10 to 15 years.

CLASSIFICATION OF BMD SYSTEMS

BMD systems can be classified according to the phase in which they intercept the attacking ballistic missile. The flight path of a ballistic missile is composed of three phases. An initial boost phase lasts from the time the missile is launched until it leaves the atmosphere. This phase is typically 240 seconds for Inter-Continental Ballistic Missiles (ICBMs). The boost phase is followed by a mid-course phase which covers the period of time during which the missile is outside the atmosphere, accounting for over 80 percent — roughly 25 to 30 minutes — of an ICBM's flight time.[1] Finally, the missile enters a terminal phase as it reenters the atmosphere and closes on its target. This final phase typically lasts about

1. William Schneider, Jr., et al., *U.S. Strategic Nuclear Policy and Ballistic Missile Defense: The 1980s and Beyond* (Cambridge: Institute for Foreign Policy Analysis (IFPA), 1980), p. 41.

15 seconds. The following are the advantages and disadvantages inherent in BMD interception of ballistic missiles during each of the three flight phases.

Boost Phase Interception

Advantages:

(1) The attacking missile is large, slow and "soft" (i.e., it has not yet deployed multiple reentry vehicles (RVs) or penetration aids).[2]

(2) The missile case and engine are particularly vulnerable during the highly stressed powered portion of the missile's flight trajectory.[3]

(3) Creating a small velocity or directional error in the attacking missile during this phase results in a much greater miss distance at the far end of the missile's trajectory.[4]

(4) Considerable "leverage" (i.e., the ratio of enemy RV's to BMD defensive units required to overcome the BMD system) is achieved by destroying the missile before it can deploy its Multiple Independently targeted Reentry Vehicles (MIRVs). It is far easier to deal with one booster early on than with as many as 10 attacking RVs in later portions of the missile's flight path.[5]

Disadvantage:

Boost phase defense systems would almost certainly operate from space. This entails the considerable cost of lifting the BMD components into space.

Mid-course Phase Interception

Advantages:

Because of the relatively long time for interception the threat "cloud" of attacking missiles can be analyzed and dissected. The extended time frame also allows human-directed control centers to launch successive waves of intercepting missiles in response to the structure of an ongoing attack.[6]

Disadvantage:

The attacking missiles can make use of penetration aids such as chaff and decoy projectiles to confuse the defense.

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2. Ibid., p. 43.
3. Barry J. Smernoff, "Strategic and Arms Control Implications of Laser Weapons: A Preliminary Assessment," *Air University Review* 29 (January-February 1978): 38-50.
4. Richard L. Garwin, "Are we on the verge of an arms race in space?," *Bulletin of the Atomic Scientists* 37 (May 1981): 48-53.
5. Schneider, et al., *U.S. Strategic Nuclear Policy*, p. 26.
6. William A. Davis, Jr., "Ballistic Missile Defense into the Eighties," *National Defense* (September-October 1979): 55-63.

Terminal Phase Interception[7]

Advantages:

1) Decoys and chaff are "filtered out" as they fall through the atmosphere at a slower rate than the attacking RVs.

2) RVs falling through the atmosphere provide observable wakes that aid in discrimination.

3) Attacking RVs are slowed down as they penetrate the atmosphere, and thus are easier to track or intercept.

Disadvantages:

1) The computers directing the BMD system must operate in an extremely compressed time frame (15 seconds), directing a complex network of radars and missiles in a nuclear environment.

2) Clutter from the breakup of fuel tanks makes discrimination of enemy RVs more difficult.

3) If the system fails at this point, the game is up — no human-directed actions are possible in the time frame of this phase.

BMD systems can also be classified according to the environment in which they intercept the attacking missiles and RVs. Endoatmospheric systems intercept attacking RVs within the atmosphere while exoatmospheric systems intercept attacking missiles and RVs outside the atmosphere. Terminal defense systems are endoatmospheric and mid-course defense systems are exoatmospheric. Boost phase defense systems such as satellite-based lasers would fire from an exoatmospheric position and kill the attacking missiles in both endoatmospheric and exoatmospheric environments. In general, endoatmospheric systems defend only relatively small areas, say an ICBM field, bomber base or city. Endoatmospheric defense is not able to provide concurrent defense of strategic forces and cities unless the different target sets overlap geographically. In contrast, exoatmospheric defense systems are indiscriminate in terms of their target defense potential, because of the large areas they protect.[8]

BMD TARGET SETS

The different targets BMD can defend differ in the levels of performance they require of the system. A key element in performance requirements is "leakage," the percentage of incoming RVs that manage to penetrate the defensive system. Naturally, the lower the level of leakage required, the greater the technical demands on the BMD system and, consequently,

7. Schneider, et al., *U.S. Strategic Nuclear Policy*, p. 38. The discussion of advantages and disadvantages for terminal phase interception draws on information from this source.
8. Ibid., p. 18.

the greater the cost. The following are some of the target sets BMD can defend together with their respective leakage requirements.

(1) *Single non-replaceable hardened point targets*: e.g., North American Air Defense Command (NORAD). A low to nil leakage is required since the target cannot be replaced.

(2) *Multiple hardened point targets*: e.g., the Minuteman force. Variable levels of leakage are acceptable depending upon what percentage of the target set is required to survive.

(3) *Single non-replaceable area/point soft target*: e.g., Washington D.C. and key radar installations. This is a soft counterpart to number one above. Again, low to nil leakage is required.

(4) *Multiple soft area/point targets*: e.g., cities, Strategic Air Command (SAC) bomber bases, and radars. This is a soft target counterpart to number two above. Variable levels of leakage can be endured depending upon the percentage of target losses considered acceptable.[9]

The same leakage requirement imposes a different strain on BMD systems operating in different missile flight phases. This arises from the nature of kill probabilities (Pk) and the sequential allocation of firepower in the course of an attack. For example, assume that a 10 percent leakage rate is required and that each individual intercepting missile in both terminal and mid-course defensive systems has a kill probability (Pk) of .7. Also assume an attack composed of 100 missiles. To achieve a 10 percent leakage rate the terminal defense system would have to attain a Pk of at least .9 against each attacking missile. Two defending missiles are allocated against each attacking missile with a combined Pk of .91, a total allocation of 200 defending missiles, and an expected 9 percent leakage rate. In contrast, the time span of mid-course defense allows the defending power to launch sequential defensive waves. The time between each wave's interception of the attacking missiles would be used to evaluate the effect of that wave and redirect subsequent waves. The number of waves the mid-course system could launch in such a sequential manner would be limited by its range and the promptness of its information and evaluation systems. Based on the same set of attack conditions, with time for sequential defensive waves, the mid-course defense system would launch two waves of 100 and 30 missiles, respectively. The initial wave would reduce the attacking force by 70 percent to 30 missiles. The 30 missiles in the second defensive wave would be redirected against the surviving 30 attacking missiles. The final result would be a leakage rate of only 9 percent achieved with the allocation of 130 defensive missiles.

The inability of a terminal defense system to fire more than one defensive

9. Ibid., pp. 21-22.

wave forces it to achieve high Pks against each individual attacking missile in order to maintain a low leakage rate. However, the greater length of the mid-course phase allows mid-course systems to fire a series of defensive waves, observe the effects of each defensive wave, and redirect subsequent waves to deal with the surviving attacking missiles. Boost phase defense systems such as satellite-based lasers might possess a similar capability, even given the limited time frame of this phase, because of the relatively rapid kill (frequently discussed in terms of one second or less) of such a system. The advantage of sequential wave defense can be translated into a lower overall allocation of defensive firepower or a lower required Pk for each individual round of firepower to attain any given leakage rate. This is not to say that multiple-wave defense systems can attain desired leakage rates at a lower cost than single-wave defense systems, specifically because those defense systems operating in different phases may incur different costs per wave or for given Pks for each round of firepower.[10]

Mid-course and boost phase defense systems require identical operational and technical capabilities for the defense of hard or soft targets. In the case of terminal defense, however, hard targets are easier to defend than soft targets. The constraints of hard-target terminal defense are: 1) the incoming warhead must explode near the target, and 2) the defending warhead may explode near the target. The constraints of soft-target terminal defense are: 1) the incoming warhead can explode at a distance from the target and still destroy it; and 2) the defending warhead must intercept the attacking warhead at a distance from the target in order to avoid collateral damage to the defended target, from the blast of its own warhead or the predetonation of the attacking warhead.[11] Thus, soft-target defense interception must take place at a greater distance from the target than in the case of hard-target defense. This increases the technical complexity of soft-target defense by requiring more sophisticated radars, missiles and computers. In turn, this increase in technical complexity is roughly translated into an increased overall system cost.

Based upon the technical requirements imposed by the hard/soft nature of the defended targets and the preferred level of leakage, BMD target sets can be ranked with respect to the technical sophistication they require of the defensive system:

10. In fact, mid-course firepower has been somewhat more expensive than terminal firepower historically. The cost of each Sprint terminal interceptor was $1.1 million in 1969 whereas the Spartan mid-course interceptor cost $1.5 million apiece. Abram Chayes and Jerome B. Wiesner, *ABM: An Evaluation of the Decision to Deploy an Antiballistic Missile System* (New York: Harper and Row, 1969), pp. 91, 95. This is somewhat offset by the fact that the Spartan interceptors performed area kills.
11. Schneider, et al., *U.S. Strategic Nuclear Policy*, p. 18.

(1) Multiple Hardened Point Targets (technically least demanding);
(2) Multiple Soft Area/Point Targets;
(3) Single Non-replaceable Hardened Point Target;
(4) Single Non-replaceable Soft Area/Point Target (technically most demanding).

BMD SYSTEMS

BMD systems must deal with three general problems: 1) defending the target set and successfully coping with penetration aids and countermeasures; 2) defending the BMD components themselves so as to prevent a total collapse of the system; and 3) gaining favorable cost-exchange ratios in relation to offensive systems.[12] In the following review of past, present and possible future BMD systems, emphasis is placed on the issues involved in each system's defense of target sets and the components of the system itself. A brief description of each system is provided and the particular advantages and disadvantages of each (apart from those inherent in the flight phase in which it operates) are discussed. Cost-exchange ratios are discussed following the description of the various BMD systems.

Terminal Defense Systems

A. Sprint

Sprint was the endoatmospheric layer of the original Safeguard system developed, and later dismantled, by the United States in the late 1960s and early 1970s. One Missile Site Radar (MSR) was deployed with 75 Sprint interceptors[13] armed with enhanced-radiation warheads.[14] The radar acquired attacking missiles at around 200,000 feet and a complex system directed the Sprint interceptor missiles. The time span from acquisition to interception was 15 seconds.
Disadvantages:

1) The complex mission required of the MSR resulted in its being large and expensive (about $165 million each).[15] The size of the MSR precluded effective hardening and its expense made redundant deployment undesirable. As a result, only one soft MSR was deployed for each battery of 75 Sprints. A carefully programed sequential wave attack would have targeted early waves against the MSR. Since the entire BMD system depended upon information provided by the MSR, the Sprints would have to have been

12. Adapted from ibid., p. 88.
13. Chayes and Wiesner, *ABM: An Evaluation*, p. 90.
14. Schneider, et al., *U.S. Strategic Nuclear Policy*, p. 19.
15. Chayes and Wiesner, *ABM: An Evaluation*, p. 96.

committed to the defense of the radar. Since the compressed time frame of terminal defense only allowed for one wave of defensive fire, several Sprints would have to have been allocated to intercept each attacking RV in order to have provided the MSR with even a small probability of survival. In addition, since the MSR was soft, the attacker could allocate small missiles without a hard-target kill capability, such as Submarine Launched Ballistic Missiles (SLBMs), to attack the MSR; thereby saving its heavy hard-target kill missiles for subsequent waves targeted against silos or for performing large area kills. In sum, the Sprint system could have been exhausted relatively easily in the defense of one of its own components, a single non-replaceable soft point target (technically the most demanding target set).[16] The main disadvantage of a sequential wave attack to the attacker would be the additional time it would provide the defense to launch under attack.

2) The complexity of the integrated system of computers, radars and interceptors operating in an environment replete with nuclear explosions and countermeasures in a compressed time frame raised critical questions as to its reliability.[17] It was suggested in 1969 that it might not be possible to program the necessary software,[18] and that there existed a significant probability of the entire system collapsing or misdirecting the defense in the face of an unforeseen set of attack conditions.[19]

B. *Low Altitude Defense System (LoADS)*

The Low Altitude Defense System was developed principally with MX Multiple Protective Shelter (MPS) basing in mind.[20] In many ways this system corrects for the deficiencies of the Sprint system. The LoADS consists of a small inertial guidance interceptor one half the size of the Sprint interceptor paired with small hardened radar less than one tenth the size of the MSR.[21] Each LoADS missile/radar pair defends an individual

16. Ibid., pp. 88-89.
17. Ibid., pp. 107-17.
18. Ibid., pp. 118-29.
19. Ibid., p. 110.
20. Davis, "Ballistic Missile Defense into the Eighties," p. 60.
21. Schneider, et al., *U.S. Strategic Nuclear Policy*, p. 44. The above source describes the LoADS radar as being one-tenth the size of the Site Defense Radar (a modified Sprint defensive system). The Site Defense Radar is in turn described as being smaller than the MSR in Davis, "Ballistic Missile Defense into the Eighties," p. 56. The LoADS radar has not yet been hardened for a nuclear environment, but this is considered to be easily within the reach of current technology given its small size. Davis, "Ballistic Missile Defense into the Eighties," p. 61. See also, William A. Davis, Jr., "Ballistic Missile Defense Will Work," *National Defense*, 66 (December 1981): 22.

target. Interception begins at 50,000 feet and the time available is five seconds. The LoADS is a technology with low technical risk[22] which could be available for deployment in the 1980s.[23]

Advantages:

1) By the time incoming RVs reach the low level of LoADS radar acquisition all chaff and decoys have been filtered out by the atmosphere.[24] This substantially reduces the technical sophistication required of the radar and computer.

2) The radar is only concerned with a small threat cone through which missiles aimed at its particular target must enter. This factor results in reduced computer, radar and missile requirements because the projected target and trajectory of an attacking missile is far more certain at this late stage.

3) The system was designed to be small and mobile for compatibility with MX Multiple Protective Shelter basing. Its size and mobility make it of particular relevance for the defense of a mobile Midgetman[25] or Anti-Tactical Ballistic Missile Defense (ATBM).[26]

Disadvantages:

1) Time for interception is compressed to five seconds[27] which increases the required complexity of the computer system. This increase is somewhat offset by the reductions in system complexity described above.

2) LoADS is only suitable for the defense of hardened targets. The low altitude of interception would result in collateral damage to the defended target from a predetonation of the incoming RV or from the LoADS's own warhead.

C. *Swarmjet*

The Swarmjet system would consist of four small soft radars and a set of multiple rocket launchers each armed with 500-1000 rockets. Radar acquisition would begin at 40,000 feet and interception would occur at ranges of approximately 4,000 feet.[28] Again time for interception would

22. Davis, "Ballistic Missile Defense into the Eighties," p. 61.
23. Davis, "Ballistic Missile Defense Will Work," p. 424.
24. Davis, "Ballistic Missile Defense into the Eighties," p. 61.
25. In this context it is interesting to note that Lt. General Brent Scowcroft (Ret.) and former Secretary of Defense Harold Brown testified to the effect that the Midgetman would not be survivable unless a large number were built at prohibitive cost given the current arms control environment. Hearing before the Senate Armed Services Committee on Department of Defense Authorization for Fiscal Year 1984, 98th Cong., 1st sess., 1983.
26. Davis, "Ballistic Missile Defense into the Eighties," p. 62.
27. Ibid., p. 61.
28. Daniel O. Graham, *High Frontier: A New National Strategy* (Washington: The Heritage Foundation, 1982), pp. 115-16.

be five seconds. Approximately 10,000 rockets would be needed for a high probability of kill against each incoming RV.[29]

Advantages:

1) The system would be technically simple, cheap and would use immediately available technology.[30]

2) At the Swarmjet's low altitude of interception chaff and decoys have been filtered out by the atmosphere, thereby reducing the sophistication required of the radar system.[31]

Disadvantages:

1) Because of its low altitude of interception the Swarmjet system could only defend hardened targets.

2) Shock waves of nearby nuclear explosions would drive the unguided projectiles off course.[32] The attacker could ostensibly create a nearby nuclear explosion and hit the target with another warhead during the time that the Swarmjet system would be rendered inoperative by blast effects. Considerable hardening of the attacker's RVs would be required to protect them from the resultant electromagnetic pulse and blast effects.

3) In order to keep system costs down, the four radars in the defensive system would not be hardened and would operate on a trilateration scheme in which each radar would provide only range information. The selective destruction of two of the radars on one side of the target would seriously degrade the ability of the remaining radars to provide adequate information on the range and trajectory of attacking RVs. The Swarmjet system would not be able to defend its own radars — since they would be deployed 15,000-24,000 feet away from the target and the rocket launchers would have an effective range of only 4000 feet.[33]

D. Atmospheric Defense

Atmospheric defense is a system in which nuclear devices are exploded around defended targets upon warning of an attack. A cloud of particles would rise to an altitude of 15 to 20 kilometers and wear down the heat shield of attacking RVs. The attacking RVs would then be destroyed by the reentry thermal environment.[34]

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29. Ibid., p. 116.
30. Ibid., p. 54.
31. Ibid., pp. 115-16.
32. Ibid., p. 54.
33. Ibid., p. 115-16. The High Frontier study claims that the radars would be sufficiently spaced apart so that one attacking warhead could not destroy more than one radar. However, the study presents diagrams in which radars are spaced 15,000 and 24,000 feet away from the defended target. A 10 kiloton warhead detonated at a ground zero 19,500 feet from the target (between the two radars) and at a scaled height of burst of 900 feet would provide 6 pounds per square inch (p.s.i.) of overpressure at the location of the two radars, sufficient to damage them beyond repair. Ibid.
34. Institute for Foreign Policy Analysis (IFPA), *U.S. Strategic-Nuclear Policy and Ballistic Missile*

Advantage:

Atmospheric defense would be a technologically simple defensive system.

Disadvantages:

1) Since the defensive system would rely on ground bursts, it might inflict considerable fallout-related collateral damage on the civilian population.[35]

2) Atmospheric defense would only be suitable for the defense of hardened targets.

3) The same particles that would wear down the heat shield of attacking RVs would also wear down the heat shield of any outgoing RVs launched in a counterstrike. The defensive system would create a "reverse pindown."

E. Pebble Curtain

The Pebble Curtain defense system would project ten gram pebbles 300 meters above a silo to destroy attacking RVs just before they struck the defended target.[36]

Advantage:

Pebble Curtain would be a technologically simple defense system.

Disadvantages:

1) Pebble Curtain would only be suitable for the defense of hardened targets.

2) The attacking RV could predetonate at an altitude just above 300 meters and still damage the silo, or the attacker could "salvage fuse" his warheads, i.e., arm the warheads so that they are detonated by the impact of the pebbles or any other projectile.[37]

3) Unless the Pebble Curtain launchers were numerous and hardened, the first incoming RV would destroy the defensive system or exhaust the defense and the second incoming RV would destroy the silo.[38]

F. Porcupine

In the Porcupine system rods are embedded into a package of high explosives that is launched into the path of incoming RVs and detonated. The rods are scattered in all directions and presumably would have a relatively high probability of striking the attacking RV(s).

Advantage:

Porcupine is a technologically simple defense system.

Defense: The 1980s and Beyond, A Conference Report III (Cambridge, MA: Institute for Foreign Policy Analysis, 1979), p. 17.

35. Ibid.

36. Ibid.

37. This would, however, entail considerable cost and difficulty and the risk of catastrophic failure. David S. Yost, "Ballistic Missile Defense and the Atlantic Alliance," *International Security* 7 (Fall 1982): 16.

38. IFPA, *U.S. Strategic-Nuclear Policy*, p. 17.

Disadvantages:

1) The system would only be suitable for hard-target defense.

2) Unless the Porcupine launchers were numerous and hardened, the system could be exhausted or destroyed by an attack of two or more RVs.[39]

3) As in the case of the Swarmjet system, the Porcupine high-explosive packages could be driven off course by nuclear blast effects.

G. Conclusions

Because the atmosphere filters out countermeasures such as chaff and decoys, the key problem faced by terminal defense systems is to avoid being easily exhausted in the defense of the target set and their own components. The greater the altitude of interception and the wider the area of coverage a terminal defense system attempts to provide, the larger and more sophisticated its computers, radars and missiles must be. This increases costs and makes key components of the system attractive soft targets. The problem of costs is ameliorated by the fact that a more sophisticated system covers a larger target set, which tends to lower the cost per target.[40] However, the complexity of the system raises questions about its ability to perform its mission in the compressed time frame of terminal defense.

In order to increase the overall effectiveness of terminal BMD the system components must, to an extent, be simplified, reduced in size and hardened. This is accomplished in the case of LoADS by reducing the mission objectives of the system to the defense of a single hard point target. The paired nature of LoADS missiles and radars presents no attractive "key components," unlike the Sprint or Swarmjet systems where 75 interceptors or dozens of rocket launchers can be incapacitated by the selective destruction of one or two radars. Moreover, the LoADS avoids the excessive technological simplicity which would make Swarmjet or Porcupine difficult to operate in a blast-effects-ridden nuclear environment. The LoADS is not technologically "simple" because it employs the simplest technology available, but because it employs adequate technology for a circumscribed mission.

Based upon the above discussion of terminal defense systems it would appear that the constraints operating on terminal defense systems are as follows:

39. Ibid.

40. The original Sprint system cost $107.5 million for computers, land, an MSR and 75 Sprint interceptors in 1969. Chayes and Wiesner, *ABM: An Evaluation*, p. 96. Since 1969 the price of Sprint interceptors has doubled. Stephen P. Rosen, "Safeguarding Deterrence," *Foreign Policy* No. 35 (Summer 1979): 121. Assuming that the costs of the other elements in the system have also doubled and that the 75 Sprint could be allocated to the defense of 75 targets, the current Sprint per target defense cost would be $8.2 million. This compared favorably with the LoADS per target defense cost of $8 million.

1) *Compressed Time*: A compressed time frame forces the system towards a narrower mission and reduced complexity.

2) *Component Vulnerability*: The single-wave defense permitted by the compressed time frame of terminal defense aggravates the separate problem of component vulnerability. Terminal defense systems must be hardened and without key components upon which the rest of a large system rests.

MIDCOURSE DEFENSE SYSTEMS

A. Spartan

The Spartan system was the exoatmospheric mid-course overlay of the Safeguard system. Advanced radars would locate and dissect the attacking force and Spartan multi-megaton warheads would be launched into the midst of the threat cloud.[41] The X-rays released by the warheads' explosions would destroy enemy RVs within a wide radius of the initial detonations.
Advantage:

The area kill capability of the Spartan system made it capable of destroying a large number of enemy RVs with a single defensive missile.
Disadvantages:

1) Spartan system radars could be the targets of the initial wave of a multiple-wave attack. Without its radars the system would give the defense additional time in which to launch under attack. The complexity and cost of the radars needed to discriminate RVs from chaff and decoys at great distances prevented the hardening or duplication of radar systems as a response to this potential countermeasure. However, the Spartan system was in a better position to defend its radars than the Sprint system because of its ability to launch sequential defensive waves.

2) Precursor nuclear explosions could blackout the radar preventing it from scanning beyond the range of the explosion.[42] This nuclear blackout would last anywhere from 10 to 17 minutes in the area of each nuclear explosion, depending upon the burst altitude.[43]

3) The Spartan warheads themselves would tend to blackout the system's radar.[44] The Spartan warhead carried a minimum of fission material so as to reduce, but not eliminate, this effect.[45]

4) Metallic chaff deployed by incoming RVs would confuse the radar.[46]

41. IFPA, *U.S. Strategic-Nuclear Policy*, p. 19.
42. Rosen, "Safeguarding Deterrence," pp. 114-15; Chayes and Wiesner, *ABM: An Evaluation*, p. 135.
43. Ibid., pp. 137-38.
44. Ibid., p. 88.
45. Ibid., p. 139.
46. Ibid., p. 135.

The defensive system could respond by detonating Spartan warheads in the midst of the chaff in an effort to destroy it and locate the incoming RVs. This could lead to the exhaustion of the defensive Spartan missiles.[47]

5) Metallic balloons in the shape of RVs could be deployed to further confuse the radars.[48]

6) The Spartan nuclear missile would require presidential release in order to be launched. While this would certainly be an easier decision than an order to launch a nuclear strike against the attacker's homeland, the eight to nine minutes needed for interception required that this order be given 20 minutes after early warning satellites detected a launch, and only 10 minutes after the early warning radar confirmed the attack.[49]

B. Non-Nuclear Kill MIRVs (NNK MIRVs)

The Non-Nuclear Kill MIRV system would involve a combination of radars, optical sensors and conventional defensive warheads. After early warning radar confirmed the approach of incoming missiles, an optical probe would be launched to observe the threat cloud. MIRVed conventional warhead interceptors would be launched and initially guided by the optical sensor. Each of the conventional warheads would use its own optical sensors for terminal guidance (i.e., final guidance corrections) against an attacking RV or missile. The system should be available for operation in the early 1990s.[50]

Advantages:

1) The NNK MIRV system would have considerably less stringent radar requirements than the Spartan system. The Spartan radars had to detect, track and differentiate a threat cloud with tiny radar cross sections at great distances. In the case of NNK MIRV the radar would only be needed to provide the general location of the threat cloud.[51]

2) Since the NNK MIRV system relies less on radar than the Spartan system, it would be less vulnerable to a selective wave attack directed against its radars. Optical sensors would already have been deployed in space and subsequent waves of optical sensors could be launched against further attacking waves based upon information provided by satellites.

3) Since metallic chaff and balloon decoys would lose heat faster than the more heavy and dense attacking RVs, the optical infrared sensor would be able to discriminate the attacking RVs in the threat cloud with considerable efficiency. Given this capability, the attacker would be better off fractionating

47. Rosen, "Safeguarding Deterrence," pp. 114-15.
48. Ibid.
49. Chayes and Wiesner, *ABM: An Evaluation*, p. 103.
50. Davis, "Ballistic Missile Defense Will Work," p. 42.
51. Rosen, "Safeguarding Deterrence," p. 117.

his payload into warheads rather than off-loading RVs for easily detectable decoys.[52] In general, countermeasures that are effective against radars are ineffective against optical sensors and vice versa. Thus, the combination of optical sensors on the early launch probe, NNK MIRVs and early warning (and possibly LoADS) radars would increase the resiliency of a system to countermeasures.

4) The NNK warheads would be small, light and cheap compared to BMD interceptors with nuclear warheads such as Spartan.[53] This advantage is somewhat offset by the fact that they would not be able to perform the area kills of which nuclear warheads are capable.

5) The NNK MIRV system would not require presidential release to respond to an apparent attack.

Disadvantage:

The probe and NNK MIRV launch pads, as well as command and control centers, could be made the targets of selective wave attacks. Since the probe has a limited orbital time, repeated probe launches would be needed to meet successive waves. The destruction of the probe launch pads would eliminate a component crucial to the system's ability to fight an extended battle. Naturally, such a selective wave attack, combined with the attacker's need to wait until the optical probes reentered the earth's atmosphere, would considerably increase the time available to launch a counterstrike. The system's vulnerability to a selective wave attack is significantly reduced by its ability to launch successive defensive waves which would allow it to sustain relatively low leakage rates in the defense of a key target set. The defense could reduce its vulnerability to selective wave attacks by multiplying launch points and command and control centers, deploying optical sensors in satellites (admittedly, the satellites would also be vulnerable), and providing a thick terminal defense of key launch pads and command and control centers.

C. Conclusions:

The principal advantage of a mid-course defense system is time. The expanded time frame for response enables a mid-course system to overcome countermeasures and to protect system components more easily than a terminal defense system. The advances in BMD technology that are encapsulated in the NNK MIRV system provide the possibility of an effective exoatmospheric defense in the 1990s. The combination of optical and radar sensors allows a NNK MIRV system to efficiently discriminate countermeasures such as chaff and decoys. The vulnerability of key system components, however, remains a problem.

52. Ibid.; Davis, "Ballistic Missile Defense Will Work," p. 22.
53. Rosen, "Safeguarding Deterrence," p. 118.

The key constraints operating on mid-course defense systems are as follows:

1) *Countermeasures*: The ability of the attacker to deploy chaff and decoys and blind or disrupt key defensive sensing mechanisms drives the defense towards a multiplicity of different sensors.

2) *Component Vulnerability*: Component vulnerability remains a problem in mid-course defense that is best offset by increased capabilities for selective wave defense and the multiplication of sensing mechanisms and command and control centers.

Boost Phase Defense Systems

A. Lasers

The Department of Defense defines a high energy laser as "one that has an average power output of at least 20 kilowatts or a minimum pulsed power of 30 kilojoules."[54] BMD laser systems can operate either as continuous waves or pulses of energy. A continuous wave laser would build up heat at a point on the targeted missile, burn through the outer structure and subsequently burn key electronic equipment within the guidance package or ignite the booster fuel. A pulsed laser would, in addition to the above, create a shock wave on the target surface. The X-ray radiation from the vaporized metal surface would cause structural and electronic damage.[55] Simple laser systems are currently in the experimental and prototype development stage.

The ideal operational environment for lasers is space. As a function of the wavelength of the laser, the atmosphere absorbs the laser energy, causes the beam to defocus ("bloom") and adds jitter to the beam.[56] Cloudiness, bad weather or smoke increase all of these effects.[57] Combined with the energy-absorbing effect of the atmosphere, this results in a lower peak intensity and increases the dwell time necessary to burn through the target's outer structure. In fact, at a "given range there is a critical power level beyond which intensity on target decreases as power radiated by the weapon increases."[58] Finally, RVs must be hardened for reentry into the atmosphere and so a terminal defense laser system operating against RVs would be far less effective than a mid-course or boost phase defense system

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54. Paul A. Chadwell, "Directed Energy Weapons," *National Defense* 64 (November-December 1979): 57.
55. Barry L. Thompson, "Directed Energy Weapons and the Strategic Balance," *Orbis* 23 (Fall 1979): 698.
56. "The U.S. High Energy Laser Program," *Military Technology* Issue 24 (June-July 1981): 89.
57. Chadwell, "Directed Energy Weapons," p. 58.
58. "The U.S. High Energy Laser Program," p. 89.

operating against missile cases.[59] In contrast, space provides no propagation problems for lasers, aids in the vacuum mechanics required to operate lasers, furnishes the only environment (a vacuum) in which ultraviolet and other particularly destructive laser wavelengths can propagate,[60] and provides lower angular tracking requirements which makes it easier for the laser beam to be held steadily on the target.[61] Laser systems operating endoatmospherically would be inferior to existing conventional systems given the state of current technology. Thus, the following analysis focuses on a hypothetical satellite-based exoatmospheric laser system.

Advantages:

1) Given the speed of laser fire compared to missiles, a laser BMD system would have considerably less demanding lead-time calculations.[62]

2) Within line-of-sight constraints the laser system could selectively attack targets among a cluster of friendly or enemy vehicles.[63]

3) Laser systems use relatively little fuel and would possess considerable fire potential.[64] This advantage is somewhat offset by the cost of lifting the laser fuel into orbit.

4) Because the laser is steered with mirrors it would have omnidirectional fire and an extremely fast slew rate.[65] (The slew rate is the speed with which the angle of fire can be changed.)

Disadvantages:

1) The coordination, command and control of a complex satellite network operating against more than a thousand missiles in a compressed time frame is difficult.

2) Even though the laser system would operate from an exoatmospheric environment it would be firing into the atmosphere. The earlier the interception, the more atmosphere the laser beam would have to traverse and the less effective it would be. If the laser system were to wait until the attacking missiles emerged from the atmosphere before concentrating its fire, i.e. operate as a mid-course defense system, it would have lost the advantage of hitting highly stressed and inflammable boosters and instead would have to deal with buses (RV carrier vehicles) loaded with

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59. Michael A. Lerner et al., "A 'Star Wars' Defense," *Newsweek*, April 4, 1983, p. 19.
60. Smernoff, "Strategic and Arms Control Implications of Laser Weapons," p. 46.
61. "The U.S. High Energy Laser Program," p. 89.
62. Laser and particle beam systems are frequently described as requiring no lead time calculations at all. Chadwell, "Directed Energy Weapons," p. 58; "The U.S. High Energy Laser Program," p. 89. This is inaccurate. In the time it takes a laser beam to travel 1000-3000 kilometers (typical engagement distances), a missile traveling at the burnout velocity of a Minuteman ICBM (24,000 km/hr) would travel 22.4-67.2 meters. Clearly, some lead time calculations would be required for precise aiming and prompt target destruction.
63. Chadwell, "Directed Energy Weapons," p. 58.
64. Ibid.
65. Ibid.; Smernoff, "Strategic and Arms Control Implications of Laser Weapons," p. 44.

hardened RVs. Electronics in the bus could be targeted, but this, compared to attacking boosters, would require considerably more accurate and discriminating aiming technology.

3) The laser system would face the problem of determining when it had mortally wounded the missile booster. This is extremely important for satellite laser systems since, to keep costs down, a small number of satellites are required to destroy the major part of a launch of over 1000 missiles in the space of a few minutes.[66] Potentially, it might take a damaged booster several seconds to depart from its trajectory.[67] In addition, the booster engines might be programed to follow a somewhat erratic launch path to confuse the kill verification sensor of the laser system.

4) A satellite-based laser BMD system could be prohibitively expensive. The question of cost is a point of extreme contention and rests not only on assumptions about cost of individual laser satellites but also on the number of laser battle stations required to perform the mission of strategic BMD. In general, those who argue that only a small number of laser satellites (24 or less) are necessary to cover the whole world probably overestimate the speed with which lasers could perform the acquisition, tracking, kill and kill assessment missions.[68] On the other hand, those who believe a large number of laser battle stations would be required (150 or more) ignore the ability of laser systems to continue firing at missiles in the mid-course phase as well as in the 240-second boost phase.[69] Furthermore, it is unclear to what level of power lasers could be developed given the limitations of mirror optics, power sources and atmospheric interference. Given the fact that much of the technology required for satellite-based laser systems has not yet been developed, it is extremely difficult to estimate potential system costs.

5) Laser battle stations would be vulnerable to a large number of countermeasures, such as:

a) The laser defense system's communications with the ground could be jammed. This could be defended against by giving the system battle management autonomy upon a signal from the ground-based command or as soon as the space system perceives a threat.

b) The communications coordinating the different elements of the laser system in space could be jammed. This countermeasure would be

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66. Typically, a 200 to 250 second boost phase launch window is discussed. IFPA, *U.S. Strategic-Nuclear Policy*, p. 20. This, however, ignores the fact that the laser system could continue to operate, albeit perhaps somewhat less effectively, against RVs and buses in space.
67. Lerner, et al., "A 'Star Wars' Defense," p. 19.
68. Malcolm Wallop, "Opportunities and Imperatives of Ballistic Missile Defense," *Strategic Review* 7 (Fall 1979): 19.
69. Garwin, "Are we on the verge of an arms race in space?," p. 52; IFPA, *U.S. Strategic-Nuclear Policy*, p. 20.

effective in the context of both ground battle management and independent space battle management.

c) Electronic countermeasures could be employed against the optical or radar sensors used in the laser system to detect and dissect the threat cloud of attacking missiles and perform kill assessment.

d) The missile could be programed to rotate slowly during launch. This would reduce the effectiveness of laser fire by spreading the laser beam energy over a greater surface area.

e) Foil shapes could be deployed in front of and behind the missile to confuse the miss detection sensor. This would only be applicable in space where the foil shapes would not be swept away by atmospheric drag.

f) Chaff could be deployed when the missile is in space to confuse the laser system's acquisition radar.[70]

g) Once in space the missile could deploy large sheets of metallic foil (or parasols) on the end of a boom that would rotate rapidly to spread the laser energy over a large surface area. The foil would reflect 99 percent of the laser light and the rear surface would be composed of a highly emissive layer that would radiate the laser-generated heat into space. This countermeasure could be defeated by irradiating the missile with two lasers simultaneously from different directions. This response could in turn be countered by the deployment of additional parasols.[71]

h) The attacking missiles could be hardened against lasers. Some analysts argue that a missile could be hardened against lasers by a factor of 10 with a sacrifice of only one or two RVs.[72] Others argue that doubling a missile's resistance to laser flux would reduce its destructive power by half.[73]

6) The laser system might become the target of a first wave in a selective wave attack. This first wave might consist of direct ascent conventional and nuclear warhead vehicles such as the American and Soviet antisatellite (ASAT) weapons currently under development, interceptors that deploy metal pellets in the orbital path of the laser battle stations that would destroy the satellite by a collision at the high velocities typical of near space, the detonation of space mines deployed near the laser stations,[74] or an attack by the attacking power's own satellite battle stations against the defending power's laser satellites. The defending laser satellites could counter intercepting missiles armed with conventional explosives, nuclear

70. Thompson, "Directed Energy Weapons and the Strategic Balance," pp. 706 -07.
71. Garwin, "Are we on the verge of an arms race in space?," p. 51. Adapted from an idea presented by Garwin for satellite defense.
72. Ibid., p. 52.
73. Wallop, "Opportunities and Imperatives," p. 20.
74. Garwin, "Are we on the verge of an arms race in space?," p. 49.

weapons or pellets by physically destroying the interceptors with their lasers as these approached the system,[75] maneuvering to avoid the interceptors,[76] interfering with the intercepting system's sensors[77] and dispersing metal pellets into the path of the oncoming ASAT system.[78] A laser system could defend itself against satellite mines by declaring a quarantine zone around its satellites. Any satellite entering such a zone would be destroyed.[79] Putting aside the political implications of such a policy, one might also question how one would determine how large a quarantine zone would be needed since it would be hard to estimate what megatonnage the attacker might decide to place in its space mines.

The problem of defending against attacking laser satellites is probably the most serious ASAT countermeasure. It has been suggested that laser battle stations could defend against attacking lasers by turning their mirrors against the incoming beams.[80] This response might not be feasible in the time frame allotted by a laser attack (kills are frequently discussed in terms of less than one second) and would be rendered ineffective by a multidirectional attack. The laser battle stations could also deploy "parasols" similar to those discussed above for the defense of attacking missiles against laser systems. This, however, would interfere with the firing mission of the satellite system. The most effective response to an attack by laser satellites would be for the defending laser satellite system to counterattack and attempt to destroy the attacking laser battle stations. Because of the relatively small numbers, predictable flight path, "soft" exterior (constrained by orbital lift costs), long flight time, sensitive electronic components of laser satellite-systems and the rapid kill capability of such systems, a space-based laser BMD is an easy target for a system like itself.

B. Particle Beams

Particle beams are pulses of electrons or ions that would release energy along a cone of penetration into a target. The target would be destroyed by high explosive (fuel) detonation, structural damage, and/or damage to its electronics.[81] It is important to emphasize that particle beam technology

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75. Any system capable of destroying more than 1000 boosters should be able to defend itself against attacking ASAT missiles.
76. In May 1977 the United States announced that two military communications satellites already had the ability to evade attacking killer satellites. Edgar O'Ballance, "Killer Satellites," *National Defense* 63 (September-October 1978): 54.
77. Garwin, "Are we on the verge of an arms race in space?," p. 49.
78. O'Ballance, "Killer Satellites," p. 54.
79. Thompson, "Directed Energy Weapons and the Strategic Balance," p. 706.
80. Wallop, "Opportunities and Imperatives," p. 20.
81. William E. Wright, "Charged Particle Beam Weapons: Should We? Could We?," *United States Naval Institute Proceedings* 105 (November 1979): 29.

is mostly in the theoretical stage and thus the following analysis concerns the theoretical advantages and disadvantages of particle beam BMD systems.[82]

Particle beams face propagation problems both in endoatmospheric and exoatmospheric environments. When a particle beam propagates through the atmosphere it loses energy in proportion to the density of the air. Under normal conditions a pulse will lose half of its energy every 200 meters. This energy heats the air around the beam, which expands and creates a channel of lower density air through which the next pulse can penetrate.[83] The particle beam literally must bore its way through the atmosphere. This reduces the effective velocity of the beam to 1000 km/sec and limits its range to one to three kilometers.[84] Propagation through the atmosphere also tends to scatter the beam's electrons. However, a large current beam would create a magnetic field that would drive the electrons closer together and keep the beam diameter down to one centimeter.[85]

Particle beams propagated exoatmospherically are also confronted with a number of technical problems. It is possible that a charged particle beam would disperse to insignificant levels over the distances within which a space-based system would have to operate. Space-based particle beams would be bent by the earth's magnetic field, which would require aiming corrections. Neutral hydrogen particle beams would not be affected by the earth's magnetic field, but would disperse rapidly and might not be capable of delivering a lethal bolt at the target range.[86]

The following discussion deals only with a space-based particle beam. However, many of the same advantages and disadvantages would apply to terminal phase particle beam defense systems.

Advantages:

1) Particle beams would be extremely lethal. This would considerably reduce the time required to burn through the target's outer structure.

2) Particle beams would require reduced lead time. In space the particle beam would propagate at the speed of light. In the atmosphere it would propagate at a respectable 1000 km/sec.

3) The combination of lethality and speed would give the particle beam a high rate of fire.

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82. In fact, John Parmentola and Kosta Tsipis (a physicist at MIT) have "questioned whether such a beam would travel more than several feet from the weapon owing to the opposing electrical charges of the beam and the weapon." Thompson, "Directed Energy Weapons and the Strategic Balance," p. 704.

83. Wright, "Charged Particle Beam Weapons," p. 30.

84. Ibid., p.33; Garwin, "Are we on the verge of an arms race in space?," pp. 51-52.

85. Wright, "Charged Particle Beam Weapons," p. 30.

86. Thompson, "Directed Energy Weapons and the Strategic Balance," p. 704-05.

4) Because the beam is aimed by magnets, it would have a high slew rate.[87]

5) The combination of lethality, high slew rate and high rate of fire would eliminate the possibility of saturating the beam, i.e., it could not be overwhelmed by large numbers of attacking RVs.[88]

6) Shielding would be ineffective as a countermeasure given the penetrating power of the particle beam.[89]

7) When propagated through the atmosphere much of the energy released by the particle beam's electrons would be in the form of gamma rays. This would create a cone of radiation around the beam which could damage or disrupt the arming, fusing, guidance and control electronics in attacking missiles in the case of a near miss. The short bursts characteristic of particle beams would also produce an electromagnetic pulse which would have a similar near-miss kill capability.[90]

Disadvantages:

1) The coordination, command and control of a complex satellite network operating against over a thousand missiles in a compressed time frame is a problem.

2) Any particle beam operating from space would be unable to penetrate deep enough into the atmosphere to intercept attacking missiles for most of the boost phase. This is offset by the lethality of the beam which would allow it to destroy mid-course RVs and buses as easily as it could destroy boosters. The overall time frame, however, would be reduced.

3) Particle beam weapons might weigh as much as 100 tons. Thus, it would take three or four lifts by the space shuttle to move the parts for one weapon into orbit.[91]

4) The particle beam satellite's communications with the ground or inter-satellite communications could be disrupted.[92]

5) The acquisition and targeting sensors could be susceptible to electronic countermeasures.[93]

6) Friendly electronics would have to be shielded against the beam's electromagnetic pulse. The same effect that gives the beam a near-miss kill capability against attacking missiles might damage the system itself.[94]

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87. Wright, "Charged Particle Beam Weapons," p. 33; Chadwell, "Directed Energy Weapons," p. 60.
88. Wright, "Charged Particle Beam Weapons," p. 33.
89. Ibid., p. 29.
90. Ibid., p. 30.
91. Thompson, "Directed Energy Weapons and the Strategic Balance," p. 704.
92. Ibid., p. 706.
93. IFPA, *U.S. Strategic-Nuclear Policy*, p. 19.
94. A. Skolnick, "'Charged Particle Beam Weapons: Should We? Could We?:' Comment and Discussion," *United States Naval Institute Proceedings* 105 (December 1979): 21.

7) Small variations in the earth's magnetic field, both in space and within the earth's atmosphere, would complicate the problem of correcting for the magnetic field in aiming the beam.[95]

8) Locating the beam to make directional corrections would be a problem.[96]

9) The particle beam satellite system would be an ideal target for other particle beam satellite systems. In this case the extreme lethality and rapid fire rate of a particle beam system would make it even more vulnerable to an attack by a system like itself than was the case with laser satellites. Such an attack, however, would provide additional warning to the defender to launch under attack.

C. X-Rays

A compact, low-yield nuclear device could be based in satellites. When an attacking launch is detected, the device would explode and its energy would be directed into multiple X-ray beams that would literally evaporate targets.[97] This system is entirely in the theoretical stage, with no actual experimentation or prototype development having taken place.
Advantages:

1) The X-ray beams would be extremely powerful and would be able to penetrate the atmosphere without difficulty.[98]

2) The beams would be so lethal that hardening of attacking missiles would be ineffective as protection against the X-rays.[99]
Disadvantages:

1) The problems of coordination, command and control are aggravated by the need to strike a large number of targets simultaneously.[100]

2) Each satellite in the system would have to destroy itself to defend against even a single ASAT weapon or to destroy one attacking ICBM. The system could easily be exhausted defending against a sequential attack directed against itself or the defending power's homeland. Naturally, any such sequential wave attack would provide additional time and warning for the defending power to launch under attack.

D. Global Ballistic Missile Defense (GBMD)

The Global Ballistic Missile Defense system proposed by the Heritage Foundation's High Frontier study would consist of 432 "trucks" orbiting

95. Ibid.; Thompson, "Directed Energy Weapons and the Strategic Balance," p. 705.
96. Skolnick, "Charged Particle Beam Weapons," p. 21.
97. Ronald D. Humble, "Space Warfare in Perspective," *Air University Review* 38 (July-August 1982): 84.
98. Ibid.
99. Ibid.
100. Graham, *High Frontier*, p. 140.

the earth each armed with 40 to 45 self-propelled carrier vehicles. In the event of a nuclear attack the carrier vehicles would be released and guided to intercept the attacking missiles.[101]

Advantage:

The system is based upon a massive application of relatively simple technology, at least when compared to that used by directed energy weapons.

Disadvantages:

1) The problem of coordination, command and control would be aggravated by the need for considerable lead time calculations.

2) The system's communications with the ground or with its different elements could be disrupted.

3) The system's sensors could be disrupted.

4) Although the High Frontier study claims that such a system would cost only $12.6 billion, this is based upon extremely low cost estimates for elements such as the sensors and command, control and coordination packages, etc.[102] Given the size of the system, the sophistication of the electronic sensors and computer coordination it requires, it is likely that it would be considerably more expensive.

5) As in all satellite systems, the GBMD system is a prime target for ASAT warfare. In particular, were the attacker to deploy directed-energy satellites, and launch a first-wave attack, the GBMD system would find it difficult to counterattack and would be severely degraded. The primary factor working in favor of the GBMD system in such a contingency would be the sheer number of trucks and carrier vehicles, which might allow the system to overwhelm the attacker's directed energy weapons or continue to operate in its BMD role despite substantial losses. As is always the case in sequential wave attacks, the defender would have additional time in which to launch under attack.

E. Conclusions:

Boost phase defense systems are mostly hypothetical, theoretical, or still in the experimental stage. The irony of such systems is that were all the technical issues such as propagation and coordination problems to be solved, the space-based BMD systems would still be most effective against satellite systems like themselves. Whereas a nuclear attack would consist of over 1000 missiles launched in a compressed time frame and following unpredictable flight paths, BMD satellite systems would most likely number

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101. Ibid., p. 122.
102. The High Frontier study estimates the cost of sensor and C^3 packages for each truck, its 45 carrier vehicles and each carrier vehicle's kill vehicle at $3.3 million. The carrier vehicles are estimated at $88,000 apiece (less than the cost of many Air-to-Air missiles) and research and development costs are expected to total only $1 billion. Ibid., p. 128.

less than 100 (except in the case of GBMD), carry sensitive and vulnerable equipment, have a "soft" exterior, follow predictable flight paths and provide the attacker with as long a time frame as he might need to destroy the system (within the constraints of counterattacks and nuclear escalation). Any space-based system capable of blunting a massive nuclear attack would find an assault on a parallel satellite system relatively easy work (except in the case of a GBMD assault on a directed energy satellite system).

Terminal and mid-course defense systems operate from a friendly environment and do not have the capability to attack the BMD systems of foreign powers deployed in foreign territory (which is, after all, not their mission). In contrast, space-based systems would operate in an international environment and would be capable of destroying (or being destroyed by) similar systems deployed in the same environment. Given their capabilities, space-based BMD systems would only be secure, i.e., able to eliminate the problem of component vulnerability, if all other powers were prevented from deploying similar space-based systems. In other words, the space environment would have to be converted into a home territory/friendly environment.

Technical problems aside, the key constraints determining the operational effectiveness of space-based BMD systems derive from the key problem of component vulnerability. These constraints are as follows:

1) *Foreign Capabilities*: To the extent that foreign powers possessed similar systems, the BMD system would be vulnerable.

2) *Political/Military Control*: The potential vulnerability of space-based systems to similar systems would drive the deploying power into attempting to assert a measure of political/military control over what is otherwise considered an international environment.

BMD, COST-EXCHANGE RATIOS AND LEVERAGE

A key issue in BMD is cost-exchange ratios: how many dollars of additional defensive firepower are required to offset each additional dollar of offensive firepower. If it is the case that several defensive dollars are required to offset each additional offensive dollar, then the attacker, given no arms control constraints and adequate economic resources and political will, could economically increase the size of his attacking force and overwhelm the defense. Unless the defending power has vastly superior economic resources and the political will to expend those resources on a disadvantageous offense/defense cost-exchange ratio, deployment of any BMD system in these circumstances would appear to be undesirable.[103] The following

103. Cost-exchange ratios leave out one critical value: the value of the defended target itself. This might be one of many possible reasons that would lead a country to develop a "cost inefficient" BMD system.

discussion is an attempt to determine what conditions produce favorable cost-exchange ratios.

On a one for one basis, BMD systems are not cheaper than attacking ICBM forces. The cost of an SS-9 is $25-30 million, with a marginal cost of several million for each additional warhead. The Minuteman III costs $5 million with a marginal cost of $1 million for each additional warhead. In contrast, a LoADS radar/interceptor pair would cost $8 million and a Sprint interceptor costs $2 million (not including its share of radar and computer costs which would be determined by the number of redundant radar systems included).[104] A Spartan interceptor cost $1.5 million in 1969. Clearly, terminal defense system interceptors are not significantly cheaper than the marginal cost of additional attacking RVs and may in fact be more expensive than offensive missiles because of the additional cost of supporting systems such as radars. The Spartan warhead would have achieved area kills against a number of attacking RVs and so cannot be compared on a one for one basis with offensive systems. The small conventional warheads of the NNK MIRV interceptor are described as being cheaper than nuclear-armed defensive missiles, but these conventional interceptors would not have the capability to perform area kills.[105] It is almost ludicrous to talk about cost-exchange ratios for the theoretical and experimental space-based BMD systems. It is very difficult to argue that BMD can attain favorable cost-exchange ratios on the basis of a one to one attrition of offensive systems. The ability of BMD to sustain a favorable cost-exchange ratio depends on the extent to which it can increase the system's leverage, i.e., the number of attacking RVs required to overcome a given defensive system strength.

The leverage a system can gain depends upon whether it is pursuing subtractive defense or preferential defense. In subtractive defense each threatening RV or missile is attacked. In preferential defense, however, only those RVs threatening a limited target set are defended against, the other targets in the target set are left undefended.[106] For example, assume a force of 1000 ICBMs subtractively defended by 1000 LoADS each with a Pk of 1.0 against incoming RVs which have a Pk of 1.0 against silos. To destroy the ICBM force the attacker would have to commit 2000 RVs: one RV to each silo to "soak-off" the LoADS defense and a second RV to each silo to destroy the ICBM. Now assume that a surviving counterstrike force of 250 ICBMs is considered adequate and the 1000 LoADS preferentially defend 250 of the ICBMs (four LoADS per ICBM). To be sure of a successful strike the attacker must now allocate 5000 RVs to the attack: four RVs

104. Rosen, "Safeguarding Deterrence," p. 121.
105. Ibid., p. 118.
106. Davis, "Ballistic Missile Defense Will Work," p. 17.

to each silo to soak-off any potential LoADS defense and one RV per silo to destroy the silo. Because the attacker does not know which targets are defended by the LoADS, it must allocate enough firepower to ensure that each silo would be destroyed even if it is defended by the LoADS.

In general, leverage derived from preferential defense would depend upon the following factors:

1) *The technical qualities of the defensive system*: Kill probabilities will determine the number of defensive missiles required to achieve a given Pk against an attacking missile or RV.

2) *The percentage of targets required to survive*: To vary the earlier example, if 500 ICBMs were required to survive, only two LoADS could be allocated per silo and the attacker would only require 3000 RVs for a successful strike.

3) *The existence of soft and vulnerable key components in the defensive system*: In the case of the Sprint system, all the defending missiles would have to be allocated preferentially and inefficiently to the defense of a single nonreplaceable soft target.

4) *The extent to which the target set and/or defensive system are deceptively based or mobile*: To the extent that the positions of the target set or defensive system are known, the attacker can structure his attack to take advantage of peculiar weaknesses of the system.[107] An example of an effective structured attack would be an attack on the Sprint MSR.

5) *The hard or soft nature of the targets being defended*: Soft targets require earlier interception and thus the interception of some attacking RVs not actually targeted against the preferentially defended target.

6) *The extent to which the defensive system possesses "Impact Point Prediction" capabilities*:[108] Mid-course systems would have considerable difficulty determining which of a set of closely spaced targets an attacking missile is directed against. Mid-course systems could preferentially defend regions of the defender's country. The greater the geographic separation between different target sets, the greater the leverage afforded against a *general* strike directed against all target sets. For example, a mid-course system could preferentially defend the regions of the United States containing the land-based ICBM forces and leave other population and military target sets. Such a defensive scheme would only afford leverage to the extent that the attacker's assault was spread across all the target sets.[109]

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107. Ibid., pp. 19-20.
108. Ibid., p. 17.
109. Boost phase defense systems would possess practically no Impact Point Prediction capability. However, boost phase systems could estimate probable missile targets on the basis of the size and accuracy of different missile systems. This would require highly developed discrimination technology.

7) *The extent to which the attacker needs to destroy all elements of a target set*: If, for example, 5 of 20 bomber bases are preferentially defended, but the attacker considers his air defense capabilities sufficient to blunt a counterstrike launched with the aircraft available at five bases, then the attacker would not attempt to overwhelm any potential BMD defense at each and every base. The attacker would launch a thin attack and accept the survival of five of the bomber bases as a necessary tradeoff for reduced strike requirements.

8) *The time constraint of the attacker*: In defending against countervalue attacks, the usefulness of preferential defense is limited. The attacker can strike, observe which cities were preferentially defended and allocate additional warheads to those cities as necessary in subsequent strikes. The attacker's ability to pursue such a leisurely strike plan would be constrained to the extent that the defending power possessed strategic force during the time period required by the attacker to evaluate the results of his first attack wave.

Given the above constraints, the greatest leverage would be achieved by a deceptively based hardened terminal defense system defending hardened deceptively based or mobile strategic forces. An example of this would be a LoADS-Midgetman combination. The lowest leverage would arise out of an unconcealed soft-component terminal defense system defending population centers. An example of this would be a Sprint deployment on a massive scale in the defense of cities.

From the above analysis, it would appear that mid-course defense systems possess relatively little leverage capability and therefore would be undesirable from the point of view of cost-exchange ratios. This, however, ignores the fact that leverage must be multiplied by system costs in order to determine cost-exchange ratios and that mid-course defense systems have a sizeable impact on BMD costs. In a layered defense system composed of an exoatmospheric mid-course overlay and an endoatmospheric terminal underlay, the mid-course defense system's ability to launch sequential wave defense would reduce the technical requirements for given leakage levels and increase the ability of the system to defend its components. The mid-course system would considerably reduce the magnitude of the attack the terminal defense system would have to counter in its compressed time frame. The terminal defense underlay would in turn provide an additional wave of defensive fire and the ability to provide preferential defense of closely-spaced targets. The combination of mid-course and terminal defense would maximize system cost-effectiveness on the one hand by achieving a high degree of leverage in the defense of certain target sets and on the other hand by using sequential wave defensive fire to reduce the technical requirements of the system.

CONCLUSION

This article has attempted to derive generic constraints from specific issues, rather than focus on transient technological problems. It has identified two general constraints on the feasibility of BMD systems. First, the cost-effectiveness of BMD, like that of all other weapon systems, depends upon the mission it is required to perform. This is not a surprising conclusion, but nevertheless is somewhat ignored by BMD analysts who set up "straw man" scenarios which are used to defend either the vehement rejection or the enthusiastic approval of BMD for all possible missions. Second, the key constraint on a BMD system's ability to perform its mission in a cost-effective manner is component vulnerability. In the case of terminal defense systems, such as Sprint, this emerges in the form of the vulnerability of key soft components of the system. For mid-course defense systems, the problem of component vulnerability is somewhat ameliorated by the ability of the system to launch successive waves of defensive fire. Finally, in the case of boost-phase defense systems, such as space-based lasers, the problem of component vulnerability stems from both the fact that the capabilities needed for defense against a massive ICBM attack would also allow it to decimate a similar satellite system and from the international nature of space.

If one were to select a particular BMD system and mission that maximizes BMD cost-effectiveness it would be a mobile or deceptively based hardened terminal defense system, with a mid-course overlay, in the defense of mobile or deceptively based hardened multiple targets. However, this is not to suggest that the author believes that such a system should be deployed without consideration of the strategic and arms control implications of BMD.

Since 1983 the Reagan Administration has focused increased attention on the debate over potential deployment of a Ballistic Missile Defense system. Unfortunately, little information regarding the capabilities and constraints of the proposed BMD systems has been synthesized and made available in a single source. This article provides the necessary technical data to inform the debate. It provides a foundation for the analysis of the crucial political and strategic factors which will ultimately determine whether or not the United States will deploy a BMD system, and, if it does, which type of system will be chosen.