Making Sense of Ballistic Missile Defense: An Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives

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Division on Engineering and Physical Sciences

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Preface

Current U.S. policy is to deploy as soon as technologically possible an effective National Missile Defense system capable of defending the territory of the United States against limited ballistic attack, whether accidental, unauthorized, or deliberate.[1] The Missile Defense Agency (MDA) of the U.S. Department of Defense (DOD) plays a central role in supporting the Secretary of Defense (SECDEF) in developing and fielding an integrated, layered, ballistic missile defense system.

Ballistic missile defense (BMD) considers engaging threats during the boost phase, the midcourse phase, and the terminal phase of flight. Boost-phase defense encompasses engagements during the time period when the threat booster is still accelerating. The midcourse defense layer can be divided into (1) ascent phase, when the threat system is engaged prior to apogee, and (2) descent phase, when intercept occurs after apogee. The term “early intercept” is sometimes used to describe intercept after boost in the initial portions of the ascent phase of the threat system before apogee.[2] Finally, terminal defense refers to engagements as and after warheads reenter the atmosphere and become subject to drag and reentry heating.

TERMS OF REFERENCE

The Duncan Hunter National Defense Authorization Act for Fiscal Year 2009 (Public Law 110-417) directed the SECDEF to enter into an agreement with the National Academy of Sciences (NAS) in order to conduct an independent study of concepts and systems for U.S. boost-phase missile defense compared with “non-boost”-defense alternatives.[3] Subsequent to ensuring that all the necessary contracting and industrial security requirements were met by the NAS and MDA, the two parties entered into a contract agreement and, in December 2009, the NAS president appointed the Committee on an Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives.[4] The terms of reference for the study—that is, the committee’s charge—include the following.

1. Content—the study should include:
    (a) The extent to which boost-phase missile defense is technically feasible and practical; against potential ballistic missile threats against the United States, its forces deployed abroad, and its allies;
    (b) Whether any demonstration efforts by the Department of Defense of boost-phase missile defense technology existing as of the date of the study (including the Airborne Laser and the Kinetic Energy Interceptor) have a high probability of performing a boost-phase missile defense mission in an operationally effective, suitable, and survivable manner; and

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[1] National Missile Defense Act of 1999, Public Law 106-38.

[2] Within this report, an additional term “postboost, predeployment” is used to describe engagements where the boost phase has ended but deployment of submunitions or countermeasures has not yet occurred. This phase can be very short or nonexistent for certain threat systems.

[3] A copy of the congressional tasking is provided in Appendix A. In addition, the term “systems” is used in place of “concepts and systems” throughout this report, and the term can be either present or proposed.

[4] Biographies for the committee members are provided in Appendix B. The committee includes experts with experience in industry, academia, and government—combined with many years in strategic and tactical missile and missile defense technologies, system design and analysis, program management, policy, and cost modeling of major weapon systems as well as proven track records in deployment and operational command of these systems. That experience included knowledge of the history of ballistic missile defense, its technology evolution, and programs spanning the period from Nike X, Sentinel/Safeguard to the present.

(c) Comparison of effectiveness, limitations and relative life cycle cost with other existing or anticipated alternatives that engage missiles in other phases of their flight.

2. Boost-Phase Systems to be examined—the study should include:
   (a) The Airborne Laser;
   (b) The Kinetic Energy Interceptor (land based and sea based options); and
   (c) Other existing boost-phase technology demonstration programs.

3. Factors to be evaluated in comparing boost-phase systems with other alternatives—the study should include:
   (a) Technical capability of the system(s) against scenarios identified in paragraph (4) below;
   (b) Operational issues, including operational effectiveness;
   (c) The results of key milestone tests conducted prior to preparation of the report;
   (d) Survivability;
   (e) Suitability;
   (f) Concepts of operations, including basing considerations;
   (g) Operations and maintenance support;
   (h) Command and control considerations, including timelines for detection, decision-making, and engagement;
   (i) Shortfall and debris from intercepts;
   (j) Force structure requirements;
   (k) Effectiveness against countermeasures;
   (l) Estimated cost of sustaining the system in the field;
   (m) Reliability, availability, and maintainability;
   (n) Geographic considerations, including limitations on the ability to deploy systems within operational range of potential targets; and
   (o) Cost and cost-effectiveness, including total lifecycle cost estimates.

4. Scenarios to be assessed—the study should include an assessment of each system identified in paragraph (2) above regarding the performance and operational capabilities of the system to:
   (a) Counter short-range, medium-range, and intermediate-range ballistic missile threats from rogue states to the deployed forces of the United States and its allies; and
   (b) Defend the territory of the United States against limited ballistic missile attack.

5. Comparison with non-boost systems—the study should include an assessment of the performance and operational capabilities of non-boost missile defense systems to counter the scenarios identified in paragraph (4) above. (The results under this paragraph shall be compared to the results under paragraph (4) above.) For purposes of this paragraph, non-boost missile defense systems include:
   (a) Patriot PAC-3 System and the Medium Extended Air Defense System follow-on system;
   (b) Aegis Ballistic Missile Defense System, with all variants of the Standard Missile-3 interceptor;
   (c) Terminal High Altitude Area Defense System; and
   (d) Ground-Based Midcourse Defense System.

THE COMMITTEE'S APPROACH

The committee first convened in January 2010 and held several data-gathering and report drafting meetings over an 18-month period.[5] In order to address its charge, in part, the committee received briefings from DOD, congressional staff, nongovernmental organizations, and other individuals and organizations, in classified and open sessions. In particular, the committee received many briefings and much information from MDA. Here, the committee sought and received a look into the analyses and rationales behind MDA-sponsored programs. However, the committee also utilized its own independent systems analysis and simulation and costing expertise, in addition to leveraging its members' expertise accumulated over the years in the research and development, management, and operational command of major missile defensive and offensive missile programs.

Its study is a technical one: The committee has not understood its charter to be to consider the many important policy issues presented by missile defense, including their effect on deterrence, strategic stability, arms control, alliance relations, the appropriate level of funding for missile defense relative to other priorities, and relations with Russia and China. However, its *technical* charter is a broad one. As described in the terms of reference and reiterated at the inaugural meeting, when the committee met with congressional staff, the study is to compare boost-phase missile defense systems with non-boost-phase defense systems, i.e., alternative defense systems. The committee has understood this to mean that it should consider the full range of systems, programs, and approaches and not confine its analysis to strictly boost-phase defense.

Accordingly, the committee examined portions of the current Ground-Based Midcourse Defense (GMD) system, the Aegis, Patriot (PAC-3), and Terminal High-Altitude Area Defense (THAAD) systems currently being fielded, as well as their proposed upgrades and all boost-phase missile defense systems that had been considered, including the Airborne Laser (ABL), the Kinetic Energy Interceptor (KEI), and other existing or contemplated boost-phase technology demonstrations (e.g., space-based interceptors and airborne interceptors launched from tactical air platforms). In addition, the committee examined the planned Phased Adaptive Approach (PAA)—that is, the Aegis Ballistic Missile Defense system, with all variants of the standard missile-3 interceptor given its relevance to the non-boost systems identified in the terms of reference.

The committee considered the supporting sensor requirements for the various boost-phase and non-boost systems, and each was studied to understand its utility against the criteria identified by the Congress in the terms of reference (e.g., effectiveness, resilience to countermeasures, force structure and realistic operational concepts, and life cycle cost in comparison with other alternatives).

To support the analysis of life-cycle costs, cost data on prior and current MDA-sponsorsed programs and technology efforts were gathered from various sources, including from MDA and the Congressional Budget Office, as well as programmatic and parametric data related to the development, procurement, and operating and support costs of other existing major DOD, NASA, and commercial systems with elements similar to those planned for ballistic missile defense. Armed with this analogous database of information, the committee developed "should"

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[5] A summary of the committee's meeting is provided in Appendix C. The committee met with representatives from the Office of the Secretary of Defense, Department of the Air Force, Department of the Army, Department of the Navy, U.S. Northern Command, and U.S. Strategic Command among others in DOD such as the Missile Defense Agency, as well as representatives from the Department of State, the intelligence community, government laboratories, and the industrial base. In addition, the committee travelled to Fort Greely, Alaska, to review the operational doctrine and preparedness for the limited Ground-Based Midcourse Defense (GMD) system currently in place. The committee also held an open meeting where public input could be provided.

to "will" cost-bounded range estimates for each of the boost-phase and non-boost systems examined in this report.[6]

This unclassified report is organized as follows: Chapters 1 through 4 comprise the committee's comparison of systems for U.S. boost-phase missile defense with other "non-boost" alternatives. Chapter 5 outlines a path forward, including those activities that in its judgment should be redirected or terminated, including the various supporting sensors required. Here, the committee found systems engineering and analysis that need improvement and areas where the current ballistic missile defense capability for U.S. homeland defense—the GMD—should be reevaluated and modified as necessary in order to improve its overall effectiveness to achieve the desired end state while taking proactive steps to substantially reduce future costs. Although this report is unclassified, the committee also produced a separate classified annex, which does not modify any of the report's findings and recommendations but provides supporting material for them and sets forth details of its analysis.

The months between the committee's last meeting and the publication of the unclassified report and classified annex were spent preparing the draft manuscripts, gathering additonal information, reviewing and responding to the external review comments, editing the unclassified report and classified annex, and conducting the security review needed to produce both an unclassified report and a classified annex.

In addition, the Missile Defense Agency has approved this unclassified report for public release with the following distribution statement and release number applicable: Distribution Statement A, Approved for Public Release, 12-MDA-6981.

ACKNOWLEDGMENT

The committee thanks the many briefers who presented information essential to the writing of this unclassified report and its classified annex. In particular, the committee is especially grateful to the Missile Defense Agency (MDA) staff in Washington, D.C., who facililated the committee's efforts in gathering information related to the study tasking, such as military and technical information related to the systems for U.S. boost-phase and non-boost missile defense systems. It is also appreciative of the MDA staff at Huntsville, Alabama, during a site visit, and to the operators at Fort Greely Air Force Base and the U.S. Northern Command, who shared operational and technical insights with respect to the GMD system.

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[6] The range cost estimates follow the Office of the Secretary of Defense policy guidance described in the Defense Acquisition University article "Drive Productivity Growth Through Will Cost/Should Cost Management," issued by the Acquisition Community Connection, https://acc.dau.mil/CommunityBrowser.aspx?id=400180&lang=en-US.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Michael Bennett, Congressional Budget Office,
Joseph M. Cosumano, Jr., LTG, USA (retired), Madison, Alabama,
Raymond Jeanloz, University of California, Berkeley,
William LaPlante, MITRE,
George "Pete" Nanos, VADM, USN (retired), Johns Hopkins University, Applied Physics Laboratory,
David O. Overskei, Decision Factors, Inc.,
John P. Stenbit, Oakton, Virginia, and
Larry D. Welch, Gen, USAF (retired), Institute for Defense Analyses.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John Ahearne of Sigma Xi (emeritus). Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

The tasking for the Committee on an Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives, stated in Section 232 of the Duncan Hunter National Defense Authorization Act for Fiscal Year 2009 (Public Law 110-417), is provided in Appendix A of this report.[1] In short, the congressional tasking requests an assessment of the feasibility, practicality, and affordability of U.S. boost-phase missile defense compared with that of the U.S. non-boost missile defense when (1) countering short-, medium-, and intermediate-range ballistic missile threats from rogue states to deployed forces of the United States and its allies and (2) defending the territory of the United States against limited ballistic missile attack. Box S-1 and Figure S-1 introduce some of the terminology used in this summary and the rest of the unclassified report.

To provide a context for this analysis of present and proposed U.S. boost-phase and non-boost missile defense concepts and systems, the committee considered the following to be the missions for ballistic missile defense (BMD): (1) protection of the U.S. homeland against nuclear weapons, other weapons of mass destruction (WMD), or conventional ballistic missile attacks; (2) protection of U.S. forces, including military bases, logistics, command and control facilities, and deployed forces themselves in theaters of operation against ballistic missile attacks armed with WMD or conventional munitions; and (3) protection of U.S. allies, partners, and host nations against ballistic-missile-delivered WMD and conventional weapons.[2] A fourth mission, protection of the U.S. homeland, allies, and partners against accidental or unauthorized launch, was considered as a collateral benefit of any ballistic mission defense but not as a goal that drives system requirements.[3] Consistent with U.S. policy and the congressional tasking, the committee conducted its analysis on the basis that it is *not* a mission of U.S. BMD systems to defend against large-scale deliberate nuclear attacks by Russia or China.[4] Furthermore, although not the focus of this study, it is important to recognize that any effective defense of the U.S. homeland or allies against limited ballistic missile attack, whether the attack or the defense uses kinetic or directed energy, inherently has the capability, without significant modification, to also intercept satellites passing within its field of fire. Accordingly, great care should be taken by the United States in ensuring that negotiations on space agreements not adversely impact missile defense effectiveness. Specifically, in keeping with the National Space Policy presented to Congress in 2010, the emphasis in international space agreements should be on establishing norms of behavior with respect to shared access to space and on limiting and reducing debris rather than on setting kinematic or functional constraints that would be likely to restrict defense system effectiveness.

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[1] Biographies for the committee members are provided in Appendix B.

[2] For brevity, missions (2) and (3) are usually considered together because they so often involve defense against hostile missiles of similar character, although being defended against for different purposes.

[3] Any BMD system would provide some inherent capabilities for defense against an accidental or unauthorized launch of a Russian or Chinese, or for that matter, one owned by another power. However, defense against such attacks should not drive the design or evaluation of defense concepts, because the greater sophistication (or numbers) of such an attack would tend to establish unrealistic and perhaps infeasible or unaffordable requirements compared with those appropriate for defenses focused on the rogue state threat.

[4] Aside from political and stability effects, such defense is not practical, given the size, sophistication, and capabilities of Russian and Chinese forces and both countries' potential to respond to U.S. defense efforts, including by increasing the size of the attack to the point at which defenses are simply overwhelmed by numbers. The fourth mission is discussed in greater detail in classified Appendix J).

BOX S-1
Ballistic Missile Defense Intercept Technology

For purposes of this report, ballistic missile defense intercept can occur in three phases of flight: boost phase, midcourse phase, and terminal phase. This terminology is defined below:

"Boost-phase intercept" (BPI) will be used exclusively for intercept of the threat missile prior to the end of powered flight of the main stages of the missile. Intercept during this phase is noteworthy because, if successful, the missile's payload cannot reach its intended target. Whether the payload itself survives boost-phase intercept depends on where on the target missile missile the intercept occurs. The degree of payload shortfall depends on when during the target missile's boost phase the intercept occurs. The main challenge associated with boost-phase intercept is the short time associated with powered flight, typically between 60 and 300 seconds depending on the missile's range and propellant type.

"Midcourse intercept" refers to exoatmospheric intercept after threat booster burnout. During this phase, all objects follow ballistic trajectories under the sole influence of Earth's gravitational field. The midcourse phase is noteworthy because it is the longest phase of a missile's flight (for those missiles that leave the atmosphere), thereby providing more time for observing and reacting to the threat. However, it is also the phase where decoys may be most effective because all objects follow ballistic trajectories regardless of their mass. The terms "ascent phase intercept" and "early intercept" are redundant because they refer to intercept after the end of the boost phase of flight but prior to apogee, which makes them part of midcourse intercept. Intercepting threat missiles as early as possible during the midcourse phase increases battle space and defends large footprints from a single forward site, thereby adding shot opportunities that use interceptors more efficiently.

"Terminal defense intercept" refers to endoatmospheric intercept after the midcourse defense opportunity. The presence of substantial dynamic forces make this phase unique as far as ballistic missile defense is concerned because light objects such as decoys, which slow down faster due to atmospheric drag, follow substantially different trajectories than heavy objects such as reentry vehicles. The altitude at which the transition from midcourse to terminal defense occurs is somewhat ambiguous, with light decoys being slowed appreciably relative to reentry vehicles at altitudes between 70 and 100 km and appreciable aerodynamic forces on the reentry vehicle occuring at altitudes below approximately 40 km.

NOTE: Postboost, predeployment intercept (PBDI) refers to intercept of a missile's postboost vehicle (PBV) or payload deployment module, if any, after the main rocket engines burn out and prior to the complete deployment of multiple objects contained in the missile's payload (reentry vehicles, decoys, and other countermeasures). This distinction is important because intercepts during the PBDI phase potentially eliminate some objects depending on how early in the PBDI phase the intercept occurs, PBVs are more easily detected and tracked, and PBVs may undergo lower power maneuvers as they deploy their multiple objects. The duration of the PBDI phase depends on PBV design and mission. However, it can be very or vanishingly short as noted in a recent Defense Science Board Report entitled *Science and Technology Issues of Early Intercept Ballistic Missile Defense Feasibility* (September 2011).

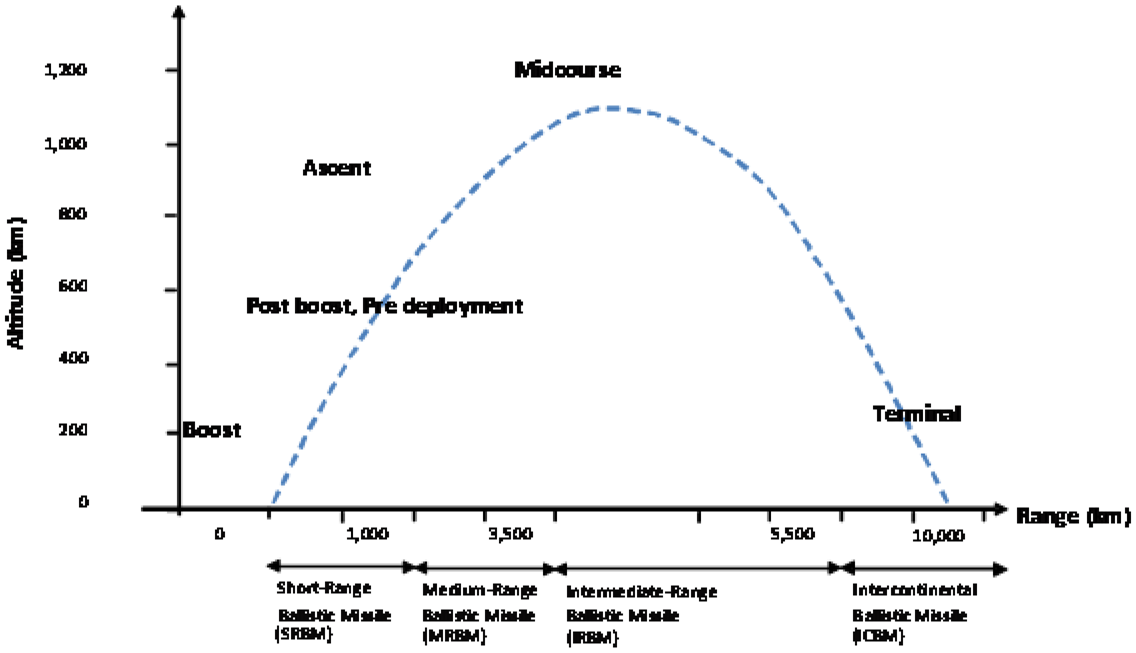

FIGURE S-1 Layered missile defense terminology.

In conducting its study, the committee received briefings from a wide variety of public and government sources and reviewed classified reports from the intelligence community and Department of Defense (DOD), in particular missile defense programs sponsored by the Missile Defense Agency (MDA).[5] Included in these briefings were, among other things, funding data for U.S. boost-phase and non-boost-phase alternatives (e.g., midcourse and terminal BMD systems). Figure S-2 displays 20-yr life-cycle costs for the BMD systems (present and proposed) examined in this report.[6] Here, the total estimated costs are broken down into development costs; acquisition plus military construction (MILCON), combined as procurement costs; operations and support (O&S) costs; and sunk investments. These costs do not include supporting sensors, which are discussed in Chapter 4 of this report.

As a starting point for the study, and to force a rigorous assessment of U.S. boost-phase and non-boost systems, as requested by the congressional tasking, the committee developed scenarios it believed the United States, and in some cases its allies, partners, and host nations, would face in each of the four missile defense missions stated in the second paragraph. These scenarios and missions are congruent with the threats described in the congressional tasking as well as with the DOD *Ballistic Missile Defense Review*.[7] In particular, as part of its analysis, the committee examined U.S. ballistic missile defense capabilities against threats from regional actors such as North Korea and Iran.

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[5] A summary of the committee's meetings is provided in Appendix C. Acronyms and abbreviations are listed in Appendix D.

[6] Chapters 2, 3, and 4 provide background information and analysis on these present and proposed BMD systems, including the operational, technical, and cost issues surrounding each. In conducting its analysis, the committee also developed two BMD systems—the continental United States (CONUS)-based, evolved Ground-Based Midcourse Defense (GMD) system and the forward-based evolved GMD system—as improvements to the current GMD system. Ultimately, the committee recommended that the MDA implement an evolutionary approach to the current GMD system, called GMD-E and discussed in detail in Chapter 5 of this report.

[7] Department of Defense. 2010. *Ballistic Missile Defense Review Report.* Washington, D.C., February.

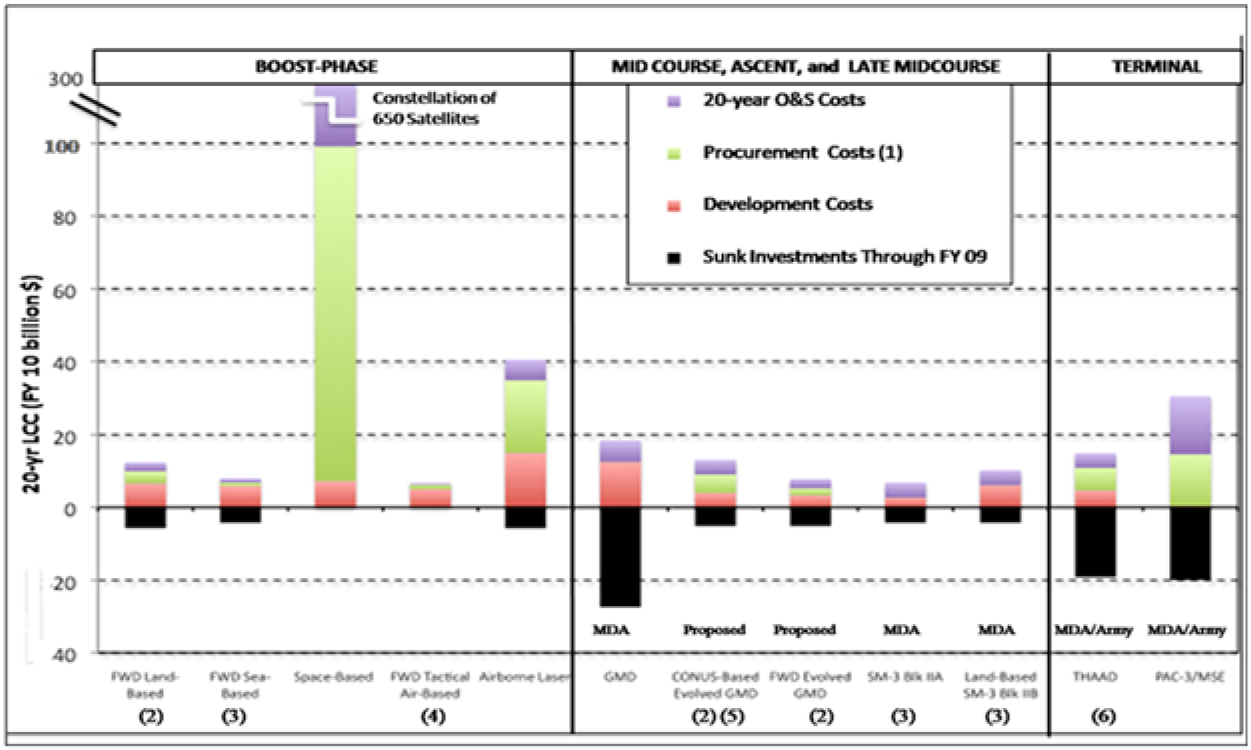

FIGURE S-2 20-yr life cycle costs for the BMD systems examined in this report. (1) Where applicable, MILCON costs included as part of procurement costs; (2) sunk investments based on kinetic energy interceptor heritage; (3) sunk investment based on Aegis block development upgrade, design, and production heritage of SM-2 Block IV; (4) CONOPS based on multimission use of retrofitted available F-15Cs and/or F-35s; (5) procurement cost includes MILCON estimates for recommended missile field and facilities infrastructure construction costs on new northeastern CONUS site; and (6) sunk investment cost for THAAD does not include separately identified past funds for AN/TPY-2 radar.

CONTEXT OF STUDY IN TODAY'S ENVIRONMENT

At the outset of the study in 2010, several decisions were taken by the Secretary of Defense (SECDEF) and reflected in the administration's defense policies; the decisions can be summarized as follows:

(1) Termination of the Kinetic Energy Interceptor (KEI) program and conversion of the Airborne Laser (ABL) program to a research and development activity in recognition of the operational and technical difficulties of intercepting missiles during the boost phase of flight.
(2) Replacement of the prior administration's proposed third site missile defense deployment in Europe by what is now known as the Phased Adaptive Approach (PAA).
(3) Termination of work on the multiple kill vehicle (MKV) technology because the threats anticipated in the next few years are not likely to be accompanied by penetration aids sophisticated enough to defeat the existing systems.
(4) Emergence of MDA's "early intercept" strategy aimed at attacking threats during or shortly after deployment of their payloads but before apogee.

For the reasons described in this report, the committee endorses decision (1) but has reservations about how (2), (3), and (4) are evolving.

Finally, while the committee sought and received a look into the analyses and rationales behind MDA-sponsored programs, it used its own independent systems analysis, simulation, and costing expertise and its expertise in many military and technical areas related to boost-phase missile defense and non-boost alternatives in order to arrive at its findings and recommendations.[8] The basis for these can be found in the unclassified report and some additional analysis can be found in the classified annex. The report's major findings and recommendations are provided in the next section.

MAJOR FINDINGS AND RECOMMENDATIONS

Findings

The committee's major findings are divided into two groups: (1) boost-phase systems and (2) non-boost-phase systems. They are summarized below and then formally articulated.

Boost-Phase Systems

The fundamental problem for boost-phase defense is that the window for intercept is short and the range of interceptors (whether propelled by kinetic or directed energy) is limited so that the platform for a boost-phase defense system must be relatively close to the threat trajectory if intercept is to be possible. Here, the duration of an attacking missile's boost phase depends on the type of fuel (solid-propellant rocket motors have significantly shorter burn times than liquid fuel ones) and the range of the threat missile (longer ranges require longer burn times). For example, an intercontinental ballistic missile (ICBM) with a liquid fuel rocket motor launched from central Iran to the U.S. East Coast would have about 250 sec of boost-phase flight (out of a total flight time of approximately 40 min), whereas an ICBM solid fuel rocket motor launched from the same location would have about 180 sec of boost-phase flight. Moreover, intercept must take place not just before burnout of the threat booster but also before it can reach a velocity that would threaten any area to be protected. For example, since boost-phase intercept is unlikely to destroy a nuclear warhead, the "debris" would not be just fragments of the attacking rocket but potentially an intact, armed nuclear weapon.

In addition to the time and range limitations associated with boost-phase defense (i.e., for a kinetic system, the distance a kinetic interceptor can cover in the time available; for a directed-energy system, the distance at which a laser beam retains sufficient power and coherence to be effective), the interceptor platform cannot for its own survivability be so close to the territory of the adversary as to be vulnerable to perimeter defenses. This constraint on platform location is particularly restrictive for airborne platforms and ships.

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[8] Four different engagement simulation models are used as part of the committee's analysis. All of them include proprietary information, although the models themselves have been validated against National Air and Space Intelligence Center detailed trajectory models, as well as industry six degree of freedom (DOF) simulations used to design and analyze ballistic missiles and interceptors. For example, one model—BMDTRADES—used to fly out threats and interceptors over a detailed oblate rotating Earth can graphically display the resulting footprint coverage and battle space. Another model, based in part on a rotating spherical Earth simulation, is used to fly out threats and interceptors from launch through the standard atmosphere using a three-DOF plus vehicle model (two translational plus one or two rotational). It is capable of graphically displaying the resulting footprint coverage and battle space. Two other two-body three-DOF plus planar engagement simulations are used to model both threat missiles and interceptors flying through the standard atmosphere with real controllability constraints, after which they are compared with the missile models used in the more global models and to cross-check the results of the first two more complex models. For this study, the committee believes the models are of sufficient detail to access accurately the capabilities and limitations of BMD systems.

There is a potentially significant qualification to this pessimistic assessment. In combat scenarios where an air supremacy has been achieved, it might be possible to maintain airborne boost-phase interceptors in intercept-effective locations that would not otherwise be feasible. This could be particularly important where the issue was defending deployed forces or friendly territory—as would be the case, for example, in a war on the Korean peninsula and in scenarios where hostile missile launches occur late enough in the war so that an opponent's air defenses have been thoroughly suppressed. Similarly, there are some threat trajectories—say, from North Korea toward Japan or Guam—where it might be feasible to station boost-phase interceptors in locations where they could be effective.[9] For almost all other plausible engagements, boost-phase intercept is not practical given the limited burn time and the requirement to be close to the intercept point. In summary, with one or two minor exceptions, land-, sea-, or air-based boost-phase defense is not feasible when timeline, range, geographical/geo-political, or cost constraints are taken into account.

Major Finding 1: While technically possible in principle, boost-phase missile defense—whether kinetic or directed energy, and whether based on land, sea, air, or in space—is not practical or feasible for any of the missions that the committee was asked to consider. This is due to the impracticalities associated with space-based boost-phase missile defense (addressed in Major Finding 2), along with geographical limits on where terrestrial (nonspace) interceptors would have to be placed and the timeline within which such interceptors must function in order to defend the intended targets.

- Intercept must take place not just before burnout of the threat booster but before it reaches a velocity that can threaten any area to be protected. Because of the short burn times of even long-range ballistic missile boosters, the interceptor launch platform cannot for its own survivability be so close to the territory of an adversary as to be vulnerable to the adversary's perimeter defenses, but it must be close enough to the boost trajectory so that the interceptor can reach the threat missile before it reaches its desired velocity.
- Surface-based boost-phase interceptors are not feasible against a large country like Iran for missiles of any kind unless the interceptor platforms are based in the southern Caspian Sea. While it has been suggested that unmanned stealthy aircraft could loiter inside or close to the borders of an adversary, the committee does not believe it to be a feasible approach against a country with an effective air defense like Russian S-300 SAMs, in the face of which stealth aircraft will have a limited time of invulnerability as they maintain station in an environment with a high-density air defense sensor.

Major Finding 2: While space basing for boost-phase defense would in principle solve the problems of geographical limits that make surface-based boost-phase intercept impractical, the size and cost of such a constellation system is extremely high and very sensitive to the timeline in which interceptors must be launched. As a result it is susceptible to countermeasures such as salvo launches that either delay and reduce its coverage or squander space-based intercepts.

- In principle, a constellation of satellites equipped with boost-phase interceptors could be configured so as always to be geographically in range for an intercept. The

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[9] For example, Aegis with SM-3 IIA on station in the East Sea could be effective in defending Hawaii and is discussed as one of three potential scenarios for intercepting hostile missiles in the boost phase of flight (see Chapter 2).

number of satellites required depends, in part, on the burn time and altitude of the threat missiles. Shorter powered flights of solid-fueled threat missiles require many more satellites for coverage. Shorter range missiles with their shorter burn times and lower burnout altitudes cannot be engaged by space-based boost-phase intercepts.

- The total life-cycle cost of placing and sustaining the constellation in orbit is at least an order of magnitude greater than that of any other alternative and impractical for that reason alone.

Non-Boost-Phase Systems

The formidable difficulties of being able to maintain boost-phase interceptors in the locations necessary to enable defense against long-range attacks mean that any operationally feasible defense against such attacks will have to effect intercept after the boost phase is complete. Moreover, while terminal defenses may provide a useful backup protection to extremely high value (or limited area) assets, the footprint limitations of terminal defenses mean that an effective defense will usually have to occur during midcourse. Furthermore, as shown in some of the engagements analyzed in Chapter 5, at best, early intercept does not occur early enough to avoid the need for midcourse discrimination.

In short, any practical missile defense system must rely primarily on intercept during the midcourse phase of flight. The attraction of midcourse (exoatmospheric) defense is that interceptors at a few sites can protect an entire country or even an entire continent, committing the first intercepts only after multiple phenomenology attack assessment. Put another way: Midcourse defense can adapt in real time to defend whatever is threatened and still have sufficient shot opportunities to deal with imperfections in target designation and with intercept failures. On the other hand, it must at some point also deal with exoamospheric countermeasures, which in principle can be light in weight yet credible and easily deployed.

The hard fact is that no practical missile defense system can avoid the need for midcourse discrimination—that is, the requirement to identify the actual threat objects (warheads) amid the cloud of material accompanying them in the vacuum of space. This discrimination is not the only challenge for midcourse defense, but it is the most formidable one, and the midcourse discrimination problem must be addressed far more seriously if reasonable confidence is to be achieved.

Decoys are not, of course, the only countermeasures a midcourse defense system must face. Other possible countermeasures include structured attacks involving simultaneous launches and/or attacks on key components of the defense, notably its sensors. As the threat evolves, defenses must adapt to these threats, as well as to increasingly sophisticated decoy-type countermeasures.[10]

The art of midcourse discrimination, developed over many decades, does not provide perfect selection of reentry vehicles. However, by designing a BMD architecture based on the capabilities described in this report, an adequate level of discrimination performance can—in the committee's judgment—be achieved in the near term and provide a reasonable chance of keeping the United States generally ahead in the contest between countermeasures and counter-

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[10] MDA has programs of record associated with sensor development with emphasis on airborne and space-based EO/IR, ground-ship-based X-band software, and the development of the SBX. For example, a notional airborne infrared sensor with a 20 cm diameter could provide precision track data to support surface-based interceptors provided two platforms are available for stereo tracking, each with LWIR sensors and low noise figures that allow for cold body detection. Tracking ranges on the order of 1,000 km should be achievable.

countermeasures over time, at least against emerging missile states like North Korea and Iran.[11] In particular, the committee believes that the best approach for addressing the midcourse discrimination problem is the synergy between X-band radar observations and optical sensors onboard the interceptors with the proper shoot-look-shoot firing doctrine described below.

The midcourse discrimination issue aside, MDA and the Services appear to be on the right track for developing BMD systems for countering short-, medium-, and intermediate-range ballistic missile threats from rogue states directed at the deployed forces of the United States and its allies. However, while Aegis, Terminal High-Altitude Area Defense (THAAD), and Patriot (PAC-3) are well developed and suited to their individual missions against these types of threats, there has been limited interface among them until recently. The committee is pleased to see that MDA is closing this gap.

Finally, there has been little evidence either of serious cost-benefit analysis or of systems analysis and engineering before embarking on new initiatives within MDA. In the committee's view, past systems proposed for U.S. boost-phase defense as well as the current GMD system architecture are classic examples. The concept of spiral development in no way justifies not defining the objectives and requirements for the desired end state. MDA's efforts have spawned an almost "hobby shop" approach, with many false starts on poorly analyzed concepts. For example, analysis of successful programs with missiles of comparable complexity—that is, with the comparison costs at a similar point of development maturity and at 2010 dollars—suggests that the current GMD interceptors are approximately 30 to 50 percent more expensive than they should be at this point in the program.

Major Finding 3: There is no practical missile defense concept or system operating before terminal phase for either the U.S. homeland or allies that does not depend on some level of midcourse discrimination, even in the absence of deliberate decoys or other countermeasures. The only alternative is to engage all credible threat objects (the Multiple Kill Vehicle program was such a hedge). Therefore it is important to face the problem of midcourse discrimination squarely and to maximize the probability of accomplishing it.

- Initially the nonthreatening objects may be "unintentional"—for example, spent upper stages, deployment modules or attitude control modules, separation debris, debris from unburned fuel, insulation, and other parts of the booster. However, as threat sophistication increases, the defense is likely to have to deal with purposeful countermeasures—decoys and other penetration aids and tactics, including salvo launches and antisimulation devices—that adversaries will have deliberately designed to frustrate U.S. defenses.
- The midcourse discrimination problem must be addressed far more seriously if reasonable confidence is to be achieved.

Major Finding 4: The synergy between X-band radar observations and concurrent optical sensor observations on board a properly designed interceptor (which could be a modified ground-based interceptor) closing on the target complex has not been exploited. The committee believes a combination of a proper operational concept and firing doctrine taking advantage of the battle space available for SLS offers the greatest potential for effective discrimination in the

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[11] There is no unequivocal answer to the question of whether a missile defense can work against countermeasures. It depends on the resources expended by the offense and the defense and the knowledge each has of the other's systems. Thus, defense effectiveness against countermeasures inevitably will vary with time as the offense-defense competition unfolds.

face of potential future countermeasures. Although it is by no means a certain solution, the committee believes this approach is not adequately exploited in current U.S. midcourse defense systems (such as GMD) and needs to be if the United States is to have an effective defense against limited attacks.

- The importance of this three-way synergy—X-band radar observations concurrent with optical sensor observations on board a properly designed interceptor together with SLS capability—cannot be overemphasized.
- This will require implementing a more realistic and robust program to gather data from flight tests and experiments (including on flights of U.S. missiles) from the full range of sensors, and making full use of the extensive data collected from past experiments to continue developing the applied science from which robust discrimination techniques and algorithms can be developed.

Major Finding 5: Based on information presented to the committee, it does not appear that MDA takes into account how the signatures of various threat objects behave when observed *concurrently* for several hundred seconds by both interceptor-mounted optical sensors closing on the threat complex and X-band radar measurements. Moreover, it appears that virtually all of the effective analytical work at MDA in optical signatures was terminated several years ago, ostensibly for budget reasons. The Midcourse Space Experiment (MSX) and the High-Altitude Observatory 2 (HALO 2) programs, for example, provided significant amounts of useful data. Yet the committee could not find anyone at MDA who could show it those data or explain them let alone the data from ground-based interceptor flight tests.

- Forty years of optical signature data from well-instrumented past and recent flight tests are lying fallow and unanalyzed with respect to current technological capabilities. These include programs with acronyms such as designating optical tracker (DOT), fly along infrared (FAIR), the Homing Overlay Experiment (HOE), the Queen Match Discrimination Experiment, and others.
- While radar and optical midcourse discrimination technologies have been pursued for years, they have largely been on separate tracks and more in competition rather than in collaboration.

Major Finding 6: To be credible and effective, a ballistic missile defense system must be robust even if any of its elements fail to work as planned, whether that failure is due to a failure of discrimination or to something else. Moreover, a properly configured midcourse defense is the most cost effective and resilient method of defending the U.S. homeland against ballistic missile attack. What is needed is a system that is resilient to failure, in particular the failure to discriminate successfully. This implies making use of SLS doctrine that exploits the potential battle space. The committee has analyzed the effectiveness of the discrimination capability of the GMD system and finds that the system can, if it works as designed, deal successfully with the initial threats from North Korea. However, the current GMD system has been developed in an environment of limited objectives (e.g., dealing with an early-generation North Korean threat of very limited numbers and capability) and under conditions where a high value was placed on getting some defense fielded as quickly as possible, even if its capability was limited and the system less than fully tested. As a result, the GMD interceptors, architecture, and doctrine have shortcomings that limit their effectiveness against even modestly improved threats and threats from countries other than North Korea. Nevertheless, 30 GMD interceptors exist (or soon will), and they and their support network of sensors—including additional properly chosen and located and already fully developed ground-based forward X-band radar elements—and communications could, at an affordable cost and on a timeline consistent with the expected threat, be modified, emplaced, and employed so as to be far more effective for the homeland defense mission.

- The foundation work for these modifications has already been done by MDA.
- For example, GMD interceptors require a Block II ground-based interceptor incorporating KEI-like booster technology having a shorter burn time and a new kill vehicle with talk-back capability to permit using downlinked information from a closing kill vehicle.

Major Finding 7: The Aegis ship-based SM-3 Block II interceptors with launch or engage on remote—both of which capabilities are under development—together with the THAAD and PAC-3 systems and their elements will provide, where appropriate, adequate coverage for defense of U.S. and allied deployed forces and of Asian allies.[12]

- With two or three Aegis ashore sites in Europe, that same combination can provide a layered late midcourse and high-altitude terminal defense for Europe.
- No interceptor with fly-out speeds less than 5.0 km/sec based in Poland or Romania or elsewhere in Europe can engage or interfere with Russia's nuclear deterrent ICBMs or submarine-launched ballistic missiles.
- Coverage of Israel and other Middle East areas against the anticipated threat will require additional Aegis and THAAD assets. (Turkey will require its separate defense using THAAD or the equivalent against shorter-range threats.) These requirements assume that single-shot defense of most areas is acceptable.
- Universal SLS capability, which is desirable for effective discrimination and other purposes, will require additional sites or terminal defense.

Major Finding 8: The first three phases of the European Phased Adaptive Approach (PAA) are expected to provide defense for Europe against a limited ballistic missile attack for deployed U.S. and allied forces within the region and the Middle East, provided the sensor architecture and the missile defense command and control (C2) center for the European PAA architecture can implement engage-on-remote capability.

- If modestly sophisticated countermeasures are anticipated for the IRBM threat, then the European PAA will need to include multiple X-band radar and long-range IR sensors (e.g., ABIR) that can provide concurrent data on IRBM trajectories similar to the countermeasures proposed for U.S. national missile defense. However, the IR data will need to come from external sensors because the SM-3 and THAAD kill vehicles have limited seeker range and limited divert capability. Fortunately, Aegis and THAAD are both capable of continuous communication between the kill vehicle and the C2 center.

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[12] In the launch-on-remote concept, the engagement is controlled and in-flight target updates are provided from the launching ship. The Aegis program is also working to develop an engage-on-remote capability by 2015, whereby (1) the interceptor can be launched using any available target track and (2) engagement is controlled from and in-flight target updates can be provided to the interceptor missile from any Aegis AN/SPY-1 or AN/TYP-2 radar. The committee applauds the MDA's progress in achieving launch-on-remote capability for Aegis.

- Europe can be covered with a SLS firing doctrine assuming enough sites are deployed, where the number of sites required depends on the interceptor speed—for example, two or three sites would be required if the interceptor speed is greater than 4.0 km/sec.
- SLS, when combined with the sensor architecture and C2 center noted above, is expected to provide a relatively robust defense of Europe against a range of potential future countermeasures.
- Turkey, as a member of NATO, will require separate BMD elements to ensure its protection. THAAD is probably the most appropriate system for this purpose owing to the stand-alone capability of its X-band radar and its ability to intercept shorter range missiles.

Major Finding 8a: Phase IV of the European PAA may not be the best way to improve U.S. homeland defense.

- The speed of the Phase IV interceptor will need to be greater than can be achieved with a 21-in. missile to avoid being overflown by lofted ICBM trajectories from Iran if the interceptor is based in northern Europe (Poland).

Major Finding 9: The proposed Precision Tracking and Surveillance System (PTSS) does not appear to be justified in view of its estimated life-cycle cost versus its contribution to defense effectiveness. Specifically, the justification provided to the committee for developing this new space-based sensor system was questionable, and the committee's analysis shows that its objective can be better accomplished by deployment of forward-based X-band radars based on the Army Navy/transportable radar surveillance model 2 (AN/TPY-2) system design at much lower total-life-cycle cost.

- The AN/TPY-2 radar already developed for THAAD and already deployed can be exploited to provide the required capabilities for all foreseeable defense missions.
- Taking advantage of the existing manufacturing base and the learning curve as more units are built would be a very cost-effective way of supporting the recommendations in this report.

Major Recommendations

The committee's major recommendations are divided into two groups: (1) boost-phase systems and (2) non-boost-phase systems.

Boost-Phase Systems

Major Recommendation 1: The Department of Defense should not invest any more money or resources in systems for boost-phase missile defense. Boost-phase missile defense is not practical or cost effective under real-world conditions for the foreseeable future.

- All boost-phase intercept (BPI) systems suffer from severe reach-versus-time-available constraints. This is true for kinetic kill interceptors launched from Earth's surface, from airborne platforms, or from space. It is also true for a directed-energy (laser) weapon in the form of the airborne laser (ABL), where reach is limited by problems of propagating enough beam over long distances in the atmosphere and focusing it onto a small spot, even with full use of sophisticated adaptive optical techniques.

- While there may be special cases of a small country such as North Korea launching relatively slow burning liquid-propellant ICBMs in which some boost-phase intercepts are possible, the required basing locations for interceptors are not likely to be politically acceptable.[13] This recommendation is not intended to preclude funding of generic research and development such as the ABL test bed, which is currently involved in boost-phase intercept, or funding of adaptive optics concepts or advances in high-power lasers that may be useful for other applications.

Non-Boost-Phase Systems

Major Recommendation 2: The Missile Defense Agency should reinstitute an aggressive, balanced midcourse discrimination research and development effort focused on the synergy between X-band radar data and concurrent interceptor observation while closing on the threat. Such an R&D effort should have the following attributes among others:

- Recognition that discrimination is strongly dependent on BMD system architecture, and known synergies should be exploited.
- A continuing program of test and analysis should be implemented to maintain the technical capacity that will be needed to support an adequate level of discrimination as new countermeasures are developed and deployed.
- A serious effort to gather and understand data from past and future flight tests and experiments (including flights of U.S. missiles) from the full range of sensors and to make full use of the extensive data collected from past experiments to generate robust discrimination techniques and algorithms.
- The committee believes that the effort required for success in this endeavor does not need to be overlarge but does require that high-quality expertise be brought to bear. The annual budget outlay, if planned correctly, can be modest compared to current expenditures.

Major Recommendation 3: The Missile Defense Agency should strengthen its systems analysis and engineering capability in order to do a better job of assessing system performance and evaluating new initiatives before significant funding is committed. Cost-benefit analysis should be central to that capability.

- In addition to terminating U.S. boost-phase missile defense systems, MDA should terminate the PTSS unless a more convincing case can be made for its efficacy for the mission that it is supposed to carry out.
- PTSS provides no information that a combination of the Space-Based Infrared System (SBIRS) and the proposed suite of X-band radars with the interceptor sensors will not provide better and at lower cost both initially and over the life cycle.

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[13] For example, while a North Korean ICBM aimed at Hawaii and some other Pacific locations could be intercepted in boost phase by a properly located Aegis ship, the United States cannot realistically or prudently expect that BPIs intended for defense against North Korean or Iranian attacks can be stationed in Russian or Chinese airspace or over other nonallied territory (or where overflights of such territory would be necessary to reach on-station locations), at least short of a full resolution of Russian and Chinese concerns about U.S. missile defense and agreement on extensive cooperation in such defense.

Moreover, as proposed, PTSS contributes little if anything to midcourse discrimination.

Major Recommendation 4: As a means to defend deployed U.S. forces and allies from short-, medium-, and intermediate-range ballistic missile threats, the Missile Defense Agency and the Services should continue investing in non-boost systems such as Aegis, THAAD, and PAC-3, with continued attention to architecture integration of sensors with shooters (sometimes referred to as an integrated battle command system, or IBCS), specifically to implement launch-on-remote (LOR) and engage-on-remote (EOR) firing doctrines.

- EOR is essential for effective coverage of Europe from a small number—say, two or three—of interceptor sites.
- Inputs to the IBCS already include those from Defense Support Program (DSP), SBIRS, and upgraded UHF early warning radars. Maximum use should be made of these data to relieve X-band radars of unnecessary volume or fan search functions, permitting them to concentrate radar resources on tracking and discrimination at the longer ranges permitted when properly cued to the targets. This involves little or no new investment. Data latency is a potential problem for the IBCS that should not be ignored.

Major Recommendation 5: As a means to provide adequate coverage for defense of the U.S. homeland against likely developments in North Korea and Iran over the next decade or two at an affordable and efficient 20-yr life-cycle cost, the Missile Defense Agency should implement an evolutionary approach to the Ground-Based Midcourse Defense (GMD) system, as recommended in this report.

- Chapter 5 recommends an evolutionary path from the present GMD system to a system having substantially greater capability and a lower cost than a simple expansion of the present GMD system. The recommended path builds on existing developments and technologies working together to make a more effective system. The concepts are not new and have been well known for at least 40 years. Existing advances in optical and radar technology will enable its realization.
- The evolutionary approach would employ smaller, lower cost, faster burning, two-stage interceptors building on development work by MDA under the KEI program carrying heavier more capable kill vehicles (KVs).
- The evolutionary approach would employ much longer concurrent threat observation by both X-band radars and the interceptor KV's onboard sensor over the entire engagement. The importance of the synergy between these concurrent observations together with SLS battle space in maximizing midcourse discrimination effectiveness cannot be overemphasized.
- An additional interceptor site with the new evolved GBI in CONUS together with the recommended radar additions provides SLS coverage of virtually the entire United States and Canada against the sort of threat that can prudently be expected to emerge from North Korea or Iran over the coming decade or so. The recommended evolution would add one additional site in the United States in the northeast, together with additional X-band radars to more effectively protect the eastern United States and Canada, particularly against Iranian ICBM threats should they emerge.

- This improved capability obviates the need for early intercept from bases in Europe, unless they are required for European defense.
- Defense of Hawaii should be provided by Aegis with launch-on-remote capability: THAAD would provide a second intercept opportunity as backup for the Aegis engagement. Hawaii is very small target area for threats from North Korea, Iran, or any other country and can be covered by one Aegis ship located west of the islands. By contrast, modifying the GMD system to provide effective defense of Hawaii against an evolved threat would add substantial complexity and cost.
- Maximize the opportunity for observing the threat complex during most of the threat trajectory until intercept. Addition of stacked TPY 2 radars are recommended for this purpose.
- Make effective use of the high-accuracy data from SBIRS to cue forward X-band radar and concurrent IR sensors on the interceptor kill vehicle, which together contribute most of the discrimination capability.
- The ability to create, communicate, and interpret target object maps (TOMs) among the radar, the battle manager, and the interceptor during the entire engagement—typically hundreds of seconds for a midcourse intercept—increases the probability of successful discrimination. The resulting TOMs with object rankings should be exchanged frequently with the interceptor kill vehicle during its fly-out. This exchange requires taking advantage of the radar’s large aperture and power to close that communication link over longer distances. The TOM’s data exchange ability builds on the capabilities demonstrated by programs such as HOE and ERIS and additionally builds on the MDA Integrated Flight Test Plan for GMD, Aegis, and THAAD interceptor that uses sensor elements with the addition of downlinks from the interceptor to the BMC3 element.

1

Introduction

BRIEF HISTORY OF BALLISTIC MISSILE DEFENSE

The potential value of defense systems deployed forward, near the launch areas of hostile ballistic missiles, was studied in the mid-1960s almost as soon as ballistic missiles were first deployed.[1] In particular, forward-based air- and sea-launched defense systems were evaluated and a space-based scheme called the Ballistic Missile Boost Intercept (BAMBI) was even proposed.

The Nike X System, which eventually led to the Sentinel and Safeguard programs, evolved from air defense missiles that were deemed the most realistic solution to defense of the continental United States (CONUS). The later systems consisted of radar-command-guided Spartan area interceptors designed to engage threats above the atmosphere, as well as radar-command-guided Sprint terminal interceptors (with very high acceleration) that were launched after atmospheric filtering of light decoys. While Sentinel was aimed at defending population and infrastructure, the system evolved into Safeguard when the objective became to defend land-based retaliatory forces.

The Safeguard program was declared operational and deployed at Grand Forks, North Dakota, at about the time the Antiballistic Missile (ABM) Treaty between the former Soviet Union and the United States was signed, but it was dismantled 2 years later. In addition to being susceptible to certain countermeasures, the Safeguard program was meant to detonate defensive nuclear warheads overhead to prevent enemy nuclear detonations in the United States, which did not engender support for it.

Even before the Safeguard program was deployed and then dismantled, the U.S. Army's Advanced Ballistic Missile Defense Agency (ABMDA) began to exploit the emerging long-wave infrared sensor technology that allowed detecting and tracking objects against the cold space background. Studies conducted in the mid- to late 1960s defined midcourse defense options based on interceptors with long-wave infrared sensors capable of detecting potential intercontinental ballistic missile (ICBM) threats thousands of kilometers away on their ballistic trajectories, observing them for more than 100 sec while closing on the threat, thereby maximizing the opportunity for discriminating warheads from countermeasures and other objects in the threat complex and finally homing on the object that posed the most credible threat to intercept it. Simulations in 1969 lent confidence to the notion that this optical homing could be accomplished with sufficient accuracy to achieve a direct hit, thereby destroying the target by the force of the collision, at closing velocities approaching or exceeding 10 km/sec. At the same time, technology was dramatically improving the ability to track rocket boosters from space and predict their trajectories with handover volumes compatible with the acquisition-and-divert capabilities of the interceptors. With a moderate-sized onboard long-wave infrared (LWIR) track (while scan or staring mosaic sensor uncapped once above 80 km altitude), the interceptor could view the threat against the deep space background as it closed in and could thus search and acquire individual objects hundreds of miles away, typically about one third the range of the threat missile. Moreover, the same sensor could be used to home on the target once it was

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[1] For additional reading, see Ashton B. Carter and David V. Schwartz, 1984, *Ballistic Missile Defense*, Brookings Institution Press, Washington, D.C.

designated to achieve miss distances consistent with nonnuclear kill. This work led to flight experiments for verification, but because of the ABM treaty, more than 10 years elapsed before a technology flight experiment—called the Homing Overlay Experiment—was initiated that led to the successful intercept of an ICBM reentry vehicle (RV) launched from Vandenberg Air Force Base in California in 1984. This experiment was followed by the Exoatmospheric Reentry Interceptor System (ERIS), which reduced the size of the kill vehicle (KV) to a more operational configuration that successfully intercepted in 1991. While all of these experimental interceptors had, in varying degrees, the onboard processing to track and discriminate among tens of objects, including celestial objects, in the field of view, there was still concern about the ease of creating relatively lightweight countermeasures that would be effective above the atmosphere.

In 2001, the National Missile Defense (NMD) program transitioned to the Ground-Based Midcourse Defense (GMD) system and was directed to be deployed by 2004. It is currently emplaced at Fort Greely, Alaska. The attraction of midcourse (exoatmospheric) defense is that interceptors at a few sites can protect targets anywhere in the entire country, committing the earliest intercepts only after assessing an attack with multiple phenomenology. Put another way, in principle, it can adapt in real time to defend against whatever is threatened and still have sufficient shot opportunities to deal with imperfections in target designation and intercept failures. On the other hand, it must at some point also deal with exoatmospheric countermeasures, which in principle can be light in weight yet credible and are easily deployed. The midcourse discrimination controversy has contributed to interest in the pursuit of boost-phase defense.

EVOLVING BALLISTIC MISSILE THREATS

Surface-to-surface ballistic missiles have proliferated in recent years. Today, many countries beside Russia and China possess such missiles. These countries include several that are hostile to the United States, notably Iran, North Korea, and Syria, and several that are not very stable. While the number of countries deploying ballistic missiles is not expected to increase dramatically in the next decade, there is a possibility that other countries whose relations with the United States are problematic could acquire them in the near future. More importantly, countries that already possess ballistic missiles are likely to improve their systems in terms of number, capability, and technological sophistication. For the purposes of this report, the committee’s analysis focused on North Korea and Iran.

So far no countries other than Russia and China (and U.S. allies such as the United Kingdom and France) have ballistic missiles of intercontinental range, although a number have space launch programs that could, in principle, be adapted for ICBM purposes. Moreover, both Iran and North Korea have deployed missiles capable of striking U.S. allies and friends and U.S. forward-deployed forces, and they are working on nuclear weapons with which to arm them and on missiles with still longer ranges.

In the case of Iran, while the regime’s long-term goals in its pursuit of ballistic missile development are unclear, it seems likely that deterrence of conventional (or nuclear) attacks on its territory and coercion of its neighbors within the Middle East are two of those goals. The growing inventory of older, liquid-propellant shorter-range missiles is a threat primarily to Iran’s closest neighbors, but the appearance longer-range liquid- and solid-propellant ballistic missiles, some with multiple stages, is a harbinger of longer-range threats to come.

Perhaps most important to this study is the rapid development of Iran’s indigenous solid-propellant missile capability. The new solid-propellant ballistic missile has an estimated range of approximately 2,000 km. All of Israel and the Arabian peninsula are within range of such a missile, as shown in Figure 1-1.[2] Here, the smaller circle represents the rotating Earth coverage of this new solid-propellant ballistic missile, or of a 2,000 km-range variant of the Shahab-3.[3] Iran is working to develop larger solid rocket motors that could soon show up as two- or three-stage IRBMs. The larger circle in Figure 1-1 shows that a notional three-stage missile employing Iran's currently-demonstrated solid-propellant technology could reach approximately 5,600 km, thus threatening virtually all of Europe, including the United Kingdom, the Eurasian landmass, and much of northern Africa. To the southeast it would reach almost to the straits of Malacca andconsiderably beyond Diego Garcia. With this capability, there may be little need to add ICBM capability to dissuade U.S. or NATO intervention to thwart Iran's ambitions.

North Korea is a somewhat different story compared to Iran. To date, it has shown little interest in long-range solid-propellant missiles, instead focusing on building bigger and more capable liquid-propellant systems. While some view the Taepo Dong 2 as a potential threat to the United States, the committee thinks this is unlikely. A more immediate threat is a new 3,200 km IRBM North Korea is developing that can threaten Japan, Guam, and Okinawa—all staging areas for a U.S. response to aggressive behavior by North Korea.[4]

An open question is whether Iran's solid propellant capability will be shared with North Korea and others in the way that liquid-propellant technology has flowed in the other direction. In this study, the committee has tried to look at the broad spectrum of threats, current or that may emerge over several years, rather than parsing the details of shifting projections of specific programs. While there is uncertainty as to the pace of either state's progress, prudence dictates that the United States assume, in the absence of verifiable evidence to the contrary, that both North Korea and Iran will eventually have ballistic missiles capable of reaching CONUS with nuclear weapons, and that both will attempt to adapt their programs to offset U.S. defense efforts. Generic but representative examples of potential ballistic missiles, available in the open

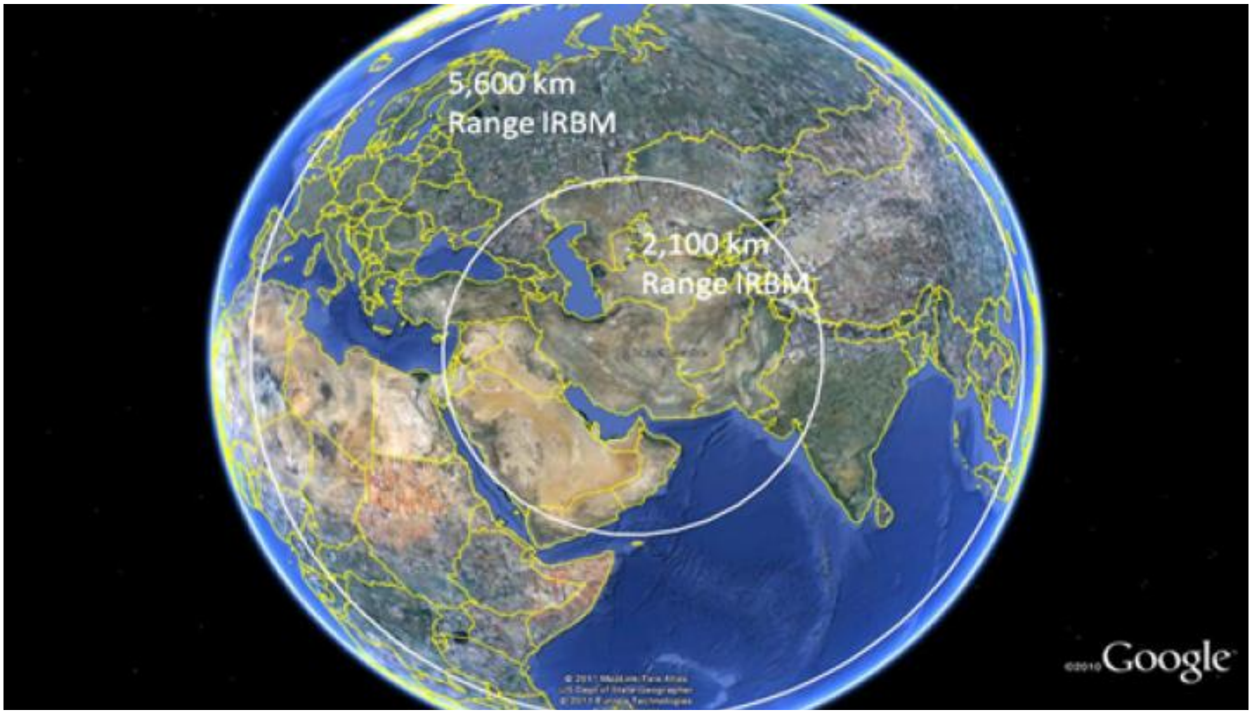

FIGURE 1-1 Hypothetical Range of Iranian ballistic missiles.

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[2] Figure 1-1 was generated from the committee's analysis using Google Earth. ©2011 Google, Map Data©2011 Tele Atlas.

[3] Department of Defense. 2010. *Ballistic Missile Defense Review Report*, February, pp. 5-6.

[4] Ibid, p. 5.

literature, and actual threat assessments from the intelligence community are provided in classified Appendix F, which accompanies this unclassified report.[5]

The principal hurdles in developing a true ICBM for Iran and North Korea to overcome are achieving reliability and a sufficient range, developing a workable RV, and producing a nuclear (or conceivably chemical or biological) weapon that can be used in an ICBM RV. Estimates of how long it will be before either country first tests an ICBM vary greatly, from a few months to a decade or more. Of course, a first test, even if successful—North Korea's initial tests of a Taepo Dong 2 nominally for space launch failed—would not be equivalent to deploying an operational system, which could take additional years. Nor is it clear how soon either country could develop a workable RV and nuclear warhead for their missiles. However, the consensus of the intelligence community is that both countries could have an operational ICBM capability within a decade.

Based on the information presented to the committee, it appears any ICBM that Iran or North Korea could deploy initially would be relatively unsophisticated. However, the U.S. intelligence community expects that most of the countries that are developing ballistic missiles will improve their capabilitiesthese missiles over time. In addition to their indigenous technological capacity, Iran and North Korea—and others seeking ballistic missile capability—are likely to be able to tap into one another's technologies and the technologies of other missile-possessing countries, whether with those countries' consent or otherwise.

In addition to increasing survivability and effectiveness of their ballistic missile force by measures such as mobile basing and increased accuracy, emerging ballistic missile states will likely make other improvements of significance for U.S. missile defense efforts, notably the adoption of solid-propellant systems, more energetic missiles, and the development and integration of countermeasures against missile defense systems. So far the countermeasure efforts of both appear to be directed against theater-level terminal defenses, but some—such as multiple near-simultaneous launches, which both Iran and North Korea have demonstrated—would also have potential against defenses designed to deal with longer-range threats.

Our nation's ability to anticipate and understand the details of an Iranian or North Korean ICBM (or other missiles) would depend substantially on the extent of their flight testing. While both countries are likely to do some testing—both to confirm the performance of their systems and in the hopes of gaining political advantage by exhibiting their prowess—they are unlikely to follow the extensive testing practices of the United States and the former Soviet Union during the Cold War or those of China.

Although Russia and China will certainly maintain and modernize their strategic nuclear arsenals, U.S. policy states that missile defense is not intended or designed to counter those forces—and any attempt to do so would be an expensive and destabilizing failure. Accordingly, and consistent with its congressional tasking, this study does not consider the ability to defend against Russian or Chinese strategic forces as an evaluation criterion for proposed missile defense systems.

In addition to developing its strategic deterrent, however, China is also very active in developing conventionally armed tactical and theater missile capabilities for "anti-access, area-denial" missions. Such missile systems could pose serious threats to U.S. allies and U.S. power projection forces in the western Pacific. A case of particular concern—though far from the only one—is the development of a much publicized anti-ship ballistic missile, with a maneuvering conventional warhead designed to attack naval forces at sea. Dealing with this potential threat is,

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[5] Some believe theater ballistic missiles launched by ships is a serious threat, particularly for nonstate actors, and there may be potential responses that would involve intercepting missiles.

in contrast to the strategic force question, very much a potential mission for U.S. missile defense.[6]

BALLISTIC MISSILE DEFENSE MISSIONS AND SYSTEMS EXAMINED

The congressional tasking for this study requested an assessment of the concepts and systems for U.S. boost-phase missile defense in comparison with non-boost ballistic missile alternatives. It calls for attention to the systems for two purposes: (1) countering short-range ballistic missile (SRBM), medium-range ballistic missile (MRBM), and intermediate-range ballistic missile (IRBM) threats from rogue states to the deployed forces of the United States and its allies; and (2) defending the territory of the United States against limited ballistic missile attack.[7]

To provide a context for analysis of present and proposed U.S. boost-phase and non-boost concepts and systems, the committee considered the following to be the missions for ballistic missile defense (BMD): (1) protection of the U.S. homeland against nuclear attacks, attacks involving other weapons of mass destruction (WMD), or conventional ballistic missile attacks; (2) protection of U.S. forces, including military bases, in theaters of operation against ballistic missile attacks armed with WMD or conventional munitions; and (3) protection of U.S. allies, partners, and host nations against ballistic-missile-delivered WMD and conventional weapons.[8] A fourth mission, protection of the U.S. homeland, allies, and partners against accidental or unauthorized launch, was considered as a collateral benefit of any ballistic mission defense but not as a goal that drives system requirements.[9] Consistent with U.S. policy and the congressional tasking, the committee conducted its analysis on the basis that it is *not* a mission of U.S. BMD systems to defend against large-scale, deliberate nuclear attacks by Russia or China.[10]

BMD intercept can, in principle, be accomplished in any of the three phases of flight of the target missile: boost phase, midcourse phase (which can in turn be subdivided into early, ascent, and postapogee or decent phases), and terminal phase. Further elaboration of this terminology is provided in Box 1-1.

Figure 1-2 displays the present and proposed U.S. BMD systems for countering SRBM, MRBM, IRBM, and ICBM threats in the context of their phases of flight.

In addressing the congressional tasking, the committee examined a wide range of present and proposed BMD systems, along with their supporting sensors. The BMD systems examined in this report are shown in Table 1-1, where they are displayed in terms of their applicability to a given protected area and mission (i.e., protecting the U.S. homeland, allies, or U.S. forces) and to a given layer of defense (terminal-, midcourse-, or boost-phase defense). The programs of record for the particular defense systems are described in Chapters 2 and 3. In addition, the committee examined two other defense systems—CONUS-based evolved GMD (denoted as

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[6] Department of Defense. 2010. *Ballistic Missile Defense Review Report*, February, p. 7.

[7] The term “systems” is used in place of “concepts and systems” throughout this report, recognizing that the term can be either existing or proposed.

[8] For brevity, missions (2) and (3) are usually considered together because they so often involve defense against hostile missiles of similar character although being defended against for different purposes.

[9] Any BMD system would provide some inherent capabilities for defense against accidental or unauthorized launch of a Russian or Chinese missile or, for that matter, one owned by another power. However, defense against such attacks should not drive the design or evaluation of defense concepts, because the greater sophistication (or numbers) of such an attack would tend to establish unrealistic and perhaps infeasible or unaffordable requirements compared to those appropriate for defenses focused on the rogue state threat.

[10] Aside from political and stability effects, such defense is not practical, given the size, sophistication, and capabilities of Russian and Chinese forces and both countries’ potential to respond to U.S. defense efforts, including by increasing the size of the attack to the point at which defenses are simply overwhelmed by numbers.

GMD-E in Chapter 5) and Forward-Based Evolved GMD—that resulted from its analysis and simulation work, where it found significant weaknesses in the current systems.

While the committee had access to classified information provided by the Missile Defense Agency on its programs of record, the committee chose to develop a set of notional threat missiles, notional interceptor designs and notional sensors to explore the basic physical limitations of missile defense system performance, with the understanding that a public report was not only requested by Congress but also helps improve public understanding of ballistic missile defense issues. As such, the analysis included in this unclassified report (as distinct from the classified appendices) is based on illustrative calculations that, in the committee's view, reasonably capture various missile defense architecture tradeoffs. None of these calculations use classified threat missiles characteristics or classified system specifications for U.S. missile defense assets.

BOX 1-1
Ballistic Missile Defense Intercept Technology

For purposes of this report, ballistic missile defense intercept can occur in three phases of flight: boost phase, midcourse phase, and terminal phase. This terminology is defined below:

"Boost-phase intercept" (BPI) will be used exclusively for intercept of the threat missile prior to the end of powered flight of the main stages of the missile. Intercept during this phase is noteworthy because, if successful, the missile's payload cannot reach its intended target. Whether the payload itself survives boost-phase intercept depends on where on the target missile missile the intercept occurs. The degree of payload shortfall depends on when during the target missile's boost phase the intercept occurs. The main challenge associated with boost-phase intercept is the short time associated with powered flight, typically between 60 and 300 seconds depending on the missile's range and propellant type.

"Midcourse intercept" refers to exoatmospheric intercept after threat booster burnout. During this phase, all objects follow ballistic trajectories under the sole influence of Earth's gravitational field. The midcourse phase is noteworthy because it is the longest phase of a missile's flight (for those missiles that leave the atmosphere), thereby providing more time for observing and reacting to the threat. However, it is also the phase where decoys may be most effective because all objects follow ballistic trajectories regardless of their mass. The terms "ascent phase intercept" and "early intercept" are redundant because they refer to intercept after the end of the boost phase of flight but prior to apogee, which makes them part of midcourse intercept. Intercepting threat missiles as early as possible during the midcourse phase increases battle space and defends large footprints from a single forward site, thereby adding shot opportunities that use interceptors more efficiently.

"Terminal defense intercept" refers to endoatmospheric intercept after the midcourse defense opportunity. The presence of substantial dynamic forces make this phase unique as far as ballistic missile defense is concerned because light objects such as decoys, which slow down faster due to atmospheric drag, follow substantially different trajectories than heavy objects such as reentry vehicles. The altitude at which the transition from midcourse to terminal defense occurs is somewhat ambiguous, with light decoys being slowed appreciably relative to reentry vehicles at altitudes between 70 and 100 km and appreciable aerodynamic forces on the reentry vehicle occuring at altitudes below approximately 40 km.

NOTE: Postboost, predeployment intercept (PBDI) refers to intercept of a missile's postboost vehicle (PBV) or payload deployment module, if any, after the main rocket engines burn out and prior to the complete deployment of multiple objects contained in the missile's payload (reentry vehicles, decoys, and other countermeasures). This distinction is important because intercepts during the PBDI phase potentially eliminate some objects depending on how early in the PBDI phase the intercept occurs, PBVs are more easily detected and tracked, and PBVs may undergo lower power maneuvers as they deploy their multiple objects. The duration of the PBDI phase depends on PBV design and mission. However, it can be very or vanishingly short as noted in a recent Defense Science Board Report entitled *Science and Technology Issues of Early Intercept Ballistic Missile Defense Feasibility* (September 2011).

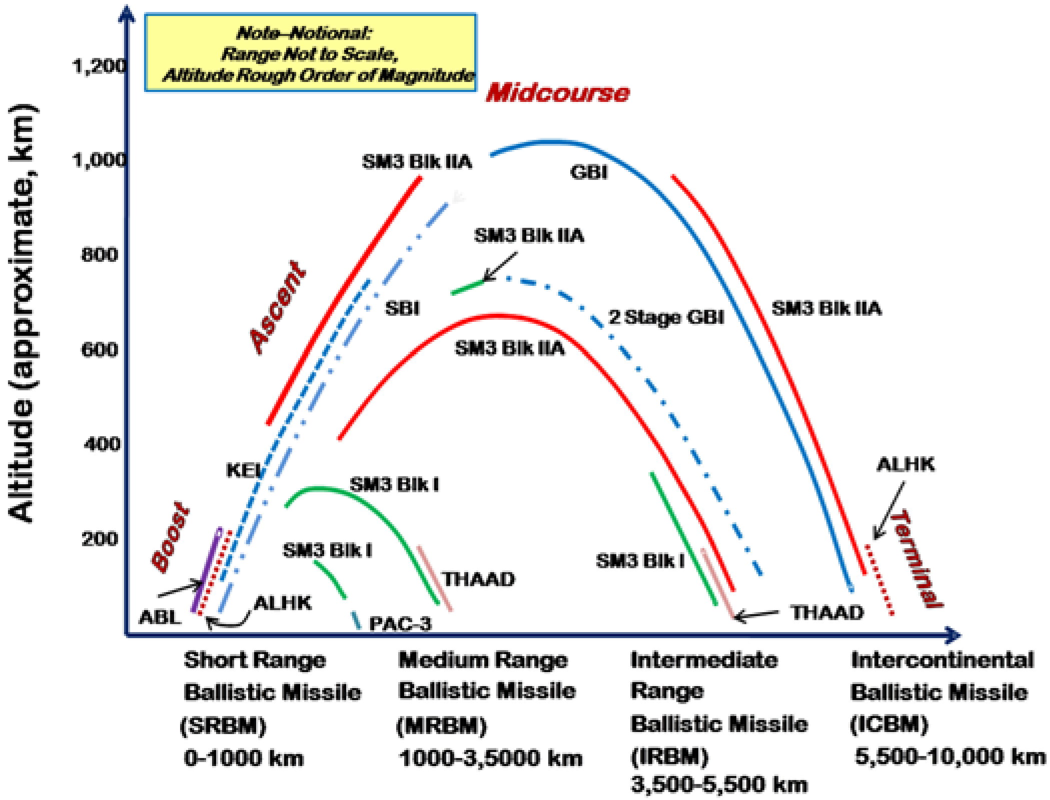

FIGURE 1-2 Notional ballistic missile defense (BMD) systems against short-range ballistic missile, medium-range ballistic missile, intermediate-range ballistic missile, and intercontinental ballistic missile threats. In this figure, all notional BMD systems are illustrated independent of their operational or developmental status. As this figure shows, numerous BMD systems have been proposed and considered for boost- and ascent-phase intercept in an attempt to build a layered defense system. PAC-3, Patriot advanced capability 3; ABI, airborne laser interceptor; GBI, ground-based interceptor.

TABLE 1-1 BMD Systems Examined in This Report in Terms of Their Potential Mission Applicability

Protected Area	Terminal	Midcourse	Ascent	Boost	Supporting Sensors
Homeland	**THAAD** **ALHK**	**GBI** **MKV** **SBI** **KEI**	**SM-3 Block IIB** **KEI** **SBI** **ALHK**	**SBI** **ABL** **KEI** **ALHK**	**DSP/SBIRS** **UEWR** **AN/TPY-2** **AN/SPY-1** **SBX** **STSS** **PTSS** **ABIR**
Allies	**SM-2 Block IV** **PAC-3** **THAAD** **MEADS**	**SM-3 Block I** **Two-stage GBI** **SM-3 Block II** **THAAD**	**SM-3 Block IIA** **SM-3 Block IIB** **KEI** **ALHK**	**ABL** **ALHK**	**DSP/SBIRS** **AN/TPY-2** **AN/SPY-1** **STSS** **PTSS** **ABIR** **Space-ISR** **A/B ISR**
Forces	**SM-2 Block IV** **PAC-3** **THAAD** **MEADS**	**SM-3 Block I** **SM-3 Block II** **THAAD**	**SM-3 Block IIA** **ALHK**	**ABL** **ALHK**	**DSP/SBIRS** **AN/TPY-2** **AN/SPY-1** **STSS** **PTSS** **ABIR** **RQ-4** **MQ-9**

NOTE: blue, operational; green, in development; purple, being considered; red, inactive, terminated, or redirected.

ORGANIZATION OF THE REPORT

Current policy guidance for missile defense is provided in three DOD reports—the 2010 *Quadrennial Defense Review*, the 2010 *Nuclear Posture Review*, and the 2010 *Ballistic Missile Defense Report*, with the last report calling for limited but effective missile defense of the U.S. homeland, of U.S. deployed forces abroad, and of the host nations for those forces. In addition, as part of U.S. policy of extended deterrence, the last of the three reports calls for cooperation with allies to provide a defense umbrella against belligerent states, particularly North Korea and Iran, that are hostile to the collective interests of the United States and its friends and allies on which it depends.

The title of this report, *Making Sense of Ballistic Missile Defense*, underscores the four primary objectives in meeting the congressional tasking. One is to provide a sound basis for resolving once and for all some of the claims for BMD systems (including sensors): Do present and proposed ballistic missile defense systems offer capability and capacity to handle situations beyond those constituted by an unrealistically constrained view of the threat? Given the kinematics and time constraints of the engagement problem, are intercepts realistically achievable? The second objective is to independently assess from a user's perspective the effectiveness and utility of the BMD systems being fielded as well as those being contemplated for future deployment. The third, as per the statement of task, is to examine the resource requirements for each BMD capability in relation to its mission utility. This resource examination is based on currently available program cost data as well as on historical cost data for systems with similar elements and takes into consideration realistic, achievable concepts of operations. The final objective is to propose a way forward for U.S. missile defense efforts, including midcourse discrimination.

The chapters of the committee's unclassified report are organized as follows: Chapter 2 provides the committee's assessment of systems for U.S. boost-phase missile defense. Chapter 3 addresses non-boost alternatives. Chapter 4 compares the various systems in terms of their utility, maturity, and cost. Chapter 5 recommends a path forward, including those activities that in the committee's judgment should be redirected or terminated and the various supporting sensors that will be required. The committee believes systems engineering and analysis need improvement and that the current ballistic missile defense capability for U.S. homeland defense—the GMD system—should evolve to improve its overall effectiveness. The committee also produced a separate classified annex, which does not modify any of the report's findings or recommendations but provides supporting material and analyses employing classified data.

2

U.S. Boost-Phase Defense

BACKGROUND

One of the primary perceived benefits of boost-phase defense is the ability to shoot down a missile during its powered phase, when it presents a bright plume signature and before it disperses its payload and countermeasures, thereby clearly identifying the target to be destroyed. This potential to overcome the midcourse discrimination problem has been among the reasons for interest in the pursuit of boost-phase defense.

The difficulty is that the boost-phase interceptor (BPI) has to be within range of a point at which it can intercept the target when launch occurs and must be able to respond with a very short action time. This turns out to be much easier said than done. Since the time from detection of a hostile launch until it completes boost is often as little as a minute and, even for slower burning liquid-fueled intercontinental ballistic missiles (ICBMs) is unlikely to exceed 250 sec, any boost-phase intercept—accomplished kinetically or by directed energy—must be launched after detection from a platform that is within the range and action time of the interceptor, essentially intercepting before "booster cut-off" of the hostile missile.

While it sounds like a good idea, boost-phase defense presents a unique set of challenges. For starters, whether a solid or liquid rocket motor is used to propel the hostile missile, the boost-phase timeline is very short. In a gross sense, the intercept process must first determine if the launch in fact is a hostile missile and, if it is, determine its trajectory. Then the vehicle providing the "kill" function—known as the kill vehicle (KV)—must acquire and shoot at the target. Here, detection range and kill range capability must be considered.

Ground- and ship-based, manned and unmanned aircraft as well as space-based interceptor platforms have all been proposed, but either the interceptor platform has to be so close to the threat launch point as to be vulnerable to attack itself, or the velocity of the intercepting projectile has to be very great. The latter is one reason for the interest in using directed-energy (speed of light) weapons for boost-phase interecept.

Today's proposed boost-phase systems originated in the Strategic Defense Initiative era's research programs. In more recent years, considerable effort has been expended in the development of an in-flight directed-energy platform—a heavily modified Boeing 747-400F airplane. Another option is destroying missiles on their launch pads prior to a suspected launch; this could have grave political consequences should an "innocent" missile be destroyed on the pad.

While boost-phase defense has been advocated as the most efficient way to deal with fractionated payloads and exoatmospheric (midcourse) penetration aids, it is extremely sensitive to assumptions about threat booster characteristics. Over time, boost-phase defense tends to be renamed ascent-phase defense when the kinematic realities set in. In fact, ascent-phase defense is code for engagement in the postboost or early midcourse phases of flight.

The limitations and complications of a surface-based boost-phase defense lie primarily in the concepts of operations (CONOPS), policy, time, and geography. Since the timelines for engagement in the boost-phase are extremely short, the on-site commander must have authorization from the National Command Authority to launch an interceptor immediately after a threat missile has been detected.[1] Also, access must be gained to countries adjacent to the threat country in order to position a boost-phase system close enough, and at the correct geometries, to successfully engage the threat missile. Finally, boost-phase systems are only effective against countries that do not have large enough landmasses to allow them to launch missiles from deep within their territory.

The airborne laser is designed to deliver energy at the speed of light to perform the boost-phase intercept mission. Space-based lasers were also pursued in the past. Virtually no fly-out time is involved, and the beam agility is a function only of how fast the pointing optics can be repositioned. While laser weapons sound like the obvious answer, the energy that a laser can deliver on a target is limited by the power available and the aperture of the device. Atmospheric effects disturb the beam. Much has been accomplished in advancing the pointing and tracking capabilities and the adaptive optics to maintain beam quality, but some fundamental limitations remain.

PROPOSED SYSTEMS

The recently redirected airborne laser (ABL) program was one of two boost-phase systems under development. While the ABL program came from over two decades of military laser development, it could not provide an operationally useful boost-phase capability, partly because the inherent range limitations of the atmospheric propagation meant that the Boeing 747-400F would need to operate in hostile airspace. An alternative approach has been to develop a kinetic kill vehicle (KKV) for boost-phase defense by harnessing the successful investments the United States has made over the past several decades for the purpose of midcourse defense, although a KKV for this purpose would have to be much more agile than a KKV for midcourse defense. The Kinetic Energy Intercept (KEI) program was undertaken for that reason. In principle, boost-phase kinetic interceptors could be launched from land-, sea-, air-, or space-based platforms. However, the efficacy of such interceptors is uncertain. In the following section the committee provides additional information on the U.S. boost-phase systems examined in this report, as called for in the congressional tasking. Specifically, the KEI and ABL programs and other existing boost-phase technology demonstration programs are first described and then analyzed.

Kinetic Energy Interceptor

The KEI program was initiated in 2002 by the Missile Defense Agency (MDA) based on a recommendation by the Defense Science Board that a boost-phase intercept capability be developed with higher average velocity (high v_{bo} and high acceleration) missiles to enhance ballistic missile defense and as an alternative to the ABL program.[2] The Office of the Under Secretary of Defense for Policy also found that a boost-phase intercept capability was required for affordability reasons. Furthermore, the ABM Treaty had recently been abrogated, making it possible to develop and deploy such a system. MDA developed a capabilities-based Request for Proposal for a transportable, ground-based boost-phase interceptor system and presented it to industry in December 2002.

The KEI program was originally funded as a $4.6 billion (in then-year dollars), 8-year development and test boost-phase system using a modified SM-3 seeker and an Exoatmospheric Kill Vehicle Divert and Attitude Control System (EKV DACS) for the KV. Immediately after the contract had been awarded, however, the funding for KEI was significantly reduced and government requirements were added. The mission was expanded in 2004 to include not only

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[1] Even if the weapons release delay is assumed to be zero, the range limits make boost-phase defense infeasible.

[2] Sean Collins, Missile Defense Agency, "Kinetic Energy Interceptor (KEI) Briefing to the National Academy of Sciences," presentation to the committee, January 14, 2010.

boost-phase intercepts but also ascent-phase (prior to countermeasure deployment) and midcourse intercepts.

The KEI program was terminated in 2009, just before a planned booster flight test. According to MDA, the threat had evolved to the point where the expected capability of the KEI system was inconsistent with the strategy for countering rogue nation threats.[3] It is also possible that extremely high costs and delays played a role in termination of the program. By that time, the KEI program had experienced mission changes coupled with technical difficulties, which led to cost growth. The projected cost to complete the contract almost doubled, from $4.6 billion to $8.9 billion (also in then-year dollars). In addition, the development schedule, originally 5½ years, was projected to take 14-16 years to complete. Over the course of the program, the average unit cost of a KEI interceptor had also increased, from $25 million to over $50 million (in then-year dollars). Prior to termination of the program, the mitigation of technical issues had delayed the first prototype booster flight test date (established in 2007) by over a year.

As shown in Figure 2-1, the KEI system consisted of a BMC2 Component, Mobile Launcher, and Interceptor All Up Round. KEI had no organic sensors but had direct access to overhead IR sensors and indirect access to other overhead national asset capabilities and to BMDS ground sensors when available.

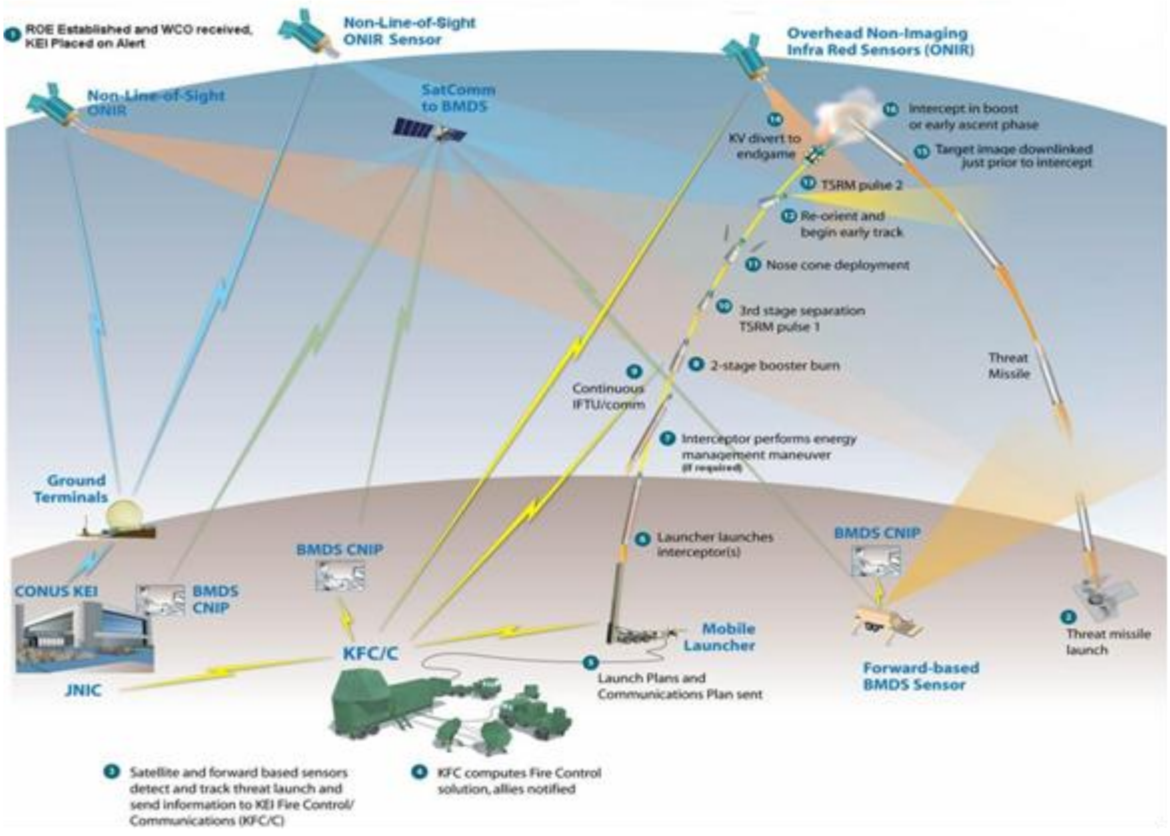

FIGURE 2-1 KEI system integration. BMDS, ballistic missile defense system; CNIP, C2BMC network interface processor; JNIC, Joint National Integration Center; ROE, rules of engagement. SOURCE: Craig van Schilfgaarde, David Theisen, Steve Rowland, and Guy Reynard, Northrop Grumman Corporation, "An Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives: Northrop Grumman Perspective," presentation to the committee, July 13, 2010. Courtesy of Northrop Grumman Corporation.

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[3] Sean Collins, Missile Defense Agency, "Kinetic Energy Interceptor (KEI) Briefing to the National Academy of Sciences," presentation to the committee, January 14, 2010.

The KEI fire unit consisted of redundant BMC2 systems that received sensor input, calculated the fire control solution, and communicated with the interceptor before and during flight. The mobile transporter erector launcher (TEL) transported and launched one round per launcher. It was transportable by C-17 or C-5A aircraft. The interceptor component was a 40-inch diameter, two-stage solid rocket. It carried a third-stage rocket motor (TSRM) in the payload that was used when additional velocity was required. The KV was a derivative of the SM-3 (two-color seeker) and the EKV DACS. It would have been capable in the boost, ascent, and midcourse intercept regions.

The CONOPS for the KEI system was very much the same as the CONOPS for tactical air and missile defense systems currently employed by the U.S. Army and the U.S. Navy. The land-based system was mobile and transportable by U.S. Air Force aircraft. The CONOPS called for KEI batteries to be garrisoned at continental United States (CONUS) locations until needed for national defense or defense of an allied country. A fire unit consisting of command and control units and 10 missile launchers with their associated transport vehicles would be transported to the theater of operations. The fire unit would move to its combat position and be emplaced. Emplacement time was estimated at approximately 3 hr. The fire unit commander would receive his rules of engagement (ROE) from his higher headquarters, which during expected periods of combat would require “Weapons Free” (authorization to fire). Upon launch of a threat missile, overhead sensors would detect and report the launch directly to the KEI fire unit. The KEI command and control system would evaluate the threat, classify it, and launch a KEI interceptor at a predicted intercept point in space. Continuous updates would be provided to the interceptor based on overhead sensor data.

Airborne Laser

The ABL program was planned to provide a boost-phase defense capability against a range of missile threats. This is no longer a program of record for the MDA but has been downgraded to a research program called the Airborne Laser Test Bed (ALTB), an advanced program for the directed-energy research program. For the purposes of this report, ABL is referred to as if it could provide an operational defense capability; where appropriate, the differences between the original ABL and the present ALTB are noted.

The attractiveness of using directed-energy weapons, notably lasers, for boost-phase defense arises out of their potential to deliver a lethal dose of damage to a target at the velocity of light from long distances. The fundamental properties on which the choice of the laser depends include the wavelength, power output, efficiency of conversion of the primary energy into laser energy, and, of course, size and weight.

So, in principle, the laser is ideal for boost-phase intercept since it is are able to project a large amount of power at the speed of light over several hundred kilometers onto a modest-sized (~1 m) spot. To capitalize on these benefits, MDA established the ABL program, which was proposed to consist of a large airframe (a modified Boeing 747-400F airplane) carrying a multimegawatt laser, known as the high-energy laser (HEL). The HEL beam is directed onto the boosting missile body for several seconds. During that time sufficient energy per unit area (fluence) is delivered to cause enough heating to result in mechanical failure of the missile body itself, thus disabling it and preventing the payload from reaching its target. The advantage of this system is that it delivers a lethal fluence to the threat missile in a matter of seconds from a great distance. Because the laser beam travels at the speed of light, the distance from which the threat can be intercepted is not limited by the flight time of a rocket interceptor. Rather, the range is limited by the fluence required, the laser power, and the ability to focus the beam onto the target at low elevation angles through the atmosphere. The ability to focus depends on the laser beam quality and issues of light propagation in the atmosphere itself. The beam propagation limitations are complex and are provided in the classified annex (Appendix J).[4]

Figure 2-2 displays key parts of the ABL system aboard the Boeing 747-400F. HELs are located in the body of the airframe, and the beam exits the plane at the nose, directed by a large (1.5-m-diameter) movable mirror in a turret.[5] The beam may be directed anywhere within a sphere with a cone cut out in the backward and forward directions with respect to the line of flight. The mirror rotates within the turret so that beam may be directed by up to about 120 deg from the line of flight.[6] The turret rotates so that any angle around the line of flight may be chosen.

The ABL must be on station near the location from which the threat missiles would be launched. One or more ABLs would orbit in figure 8-like patterns in that vicinity. Such patterns allow an advantageous side-on view of the potential threat all of the time except when the airframe must turn at the end of the 8; however, a side-on or head-on attitude is always maintained by choosing the correct direction of circulation in the 8. The ABL would fly at an altitude of approximately 12 km in order to minimize the amount of atmosphere through which the beam must travel. For redundancy and for dealing with multiple launches, two ABLs would cover one threat area. Such redundancy would be necessary during refueling operations to avoid gaps in coverage.

The ABL would operate autonomously to identify threats by means of onboard IR sensors that detect the exhaust plume of the boosting missile. With knowledge of the location of the threat, the tracking illuminator laser (TILL) is activated to acquire the target, determine the exact aim point desired using the image of the nose, and provide illumination for first-order adaptive optics (AO) corrections. (Astronomers have used AO to at least partially cancel out atmospheric disturbances.) The beacon illuminator laser (BILL) places its beam on the missile body, and that image provides the higher order correction information. Finally, the chemical

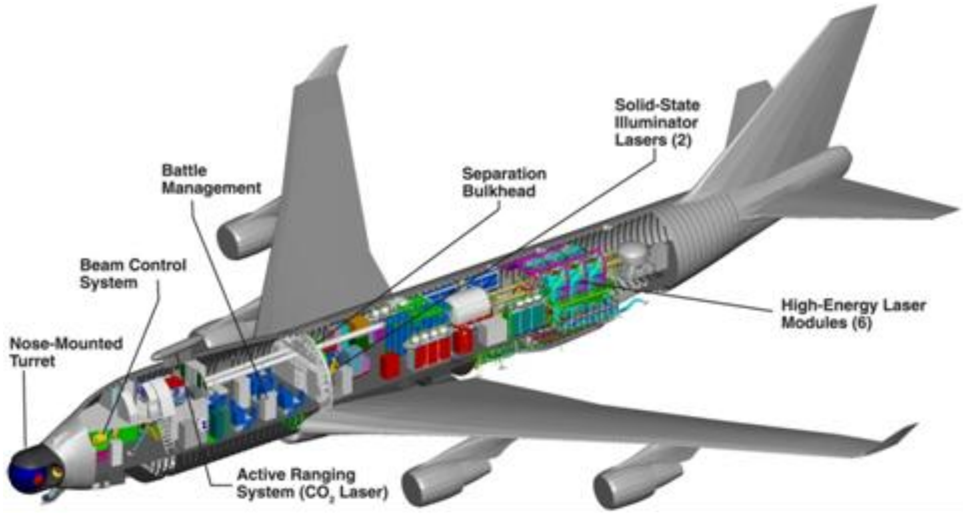

FIGURE 2-2 Cutaway of the ABL system showing its key parts. SOURCE: Col Laurence Dobrot, USAF, Missile Defense Agency, "Airborne-Laser System Program Office: Presentation to the National Academy of Sciences," presentation to the committee, January 14, 2010.

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[4] David K. Barton, Roger Falcone, Daniel Kleppner, Frederick K. Lamb, Ming K. Lau, Harvey L. Lynch, David Moncton, et al. 2004. *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues*, American Physical Society, College Park, Md., October 5.

[5] Ibid, p. S299.

[6] Ibid, p. S339.

oxygen-iodine laser (COIL) is activated with the HEL focused on the target for long enough to deliver the fluence required to induce mechanical failure of the missile. Mechanical failure results from heating a metal sufficiently to weaken it. It is not necessary to melt the metal to weaken it considerably. The failure itself may come from rupture due to pressure inside the container or from a loss of strength to resist the axial forces of acceleration of the boosting missile. There will probably be a clear optical signature of the mechanical failure to confirm the intercept. The signature may be an explosion or very erratic flight of the booster.

It is unlikely that the defense will know when a threat missile is likely to be launched. Therefore, the ABLs must be able to remain on station for extended periods. Providing continuous coverage will require in-flight refueling and a handoff to other airframes to relieve the crew or provide other maintenance for the airframe or its systems.

Other

Space-Based Interceptors

One problem of surface-based (i.e., on land, at sea, or in the air) KKVs is their access to the threat missile. There is a limit on how far a KKV can be based from the intercept point (not the launch point); this limit depends on the fly-out time of the interceptor and the burn time of the threat. A country that is large enough can deliver an array of missile threats that are not vulnerable to surface-based intercept in their boost phase. There may be political constraints on basing interceptors outside enemy territory, in neighboring countries. One way to avoid the geographic constraints suffered by surface-based interceptors is to base them in space, on platforms that carry one or several such interceptors. The enemy may thereby be denied all locations within the latitudes of the orbits. This is the attractive feature of space-based interceptors (SBIs).

At this time there is no program of record within MDA for SBIs. This report noted large differences in the size estimates of Lawrence Livermore National Laboratory's (LLNL's) KV and that of the more conservative estimate found in the 2004 American Physical Society (APS) report previously noted. The committee's assessment of these differences and their validity are discussed in the classified annex (Appendix J). In short, the committee believes the LLNL KV was much lighter because it had much less divert velocity propulsion, apparently because it separated from the booster first stage much later than did the APS KV design. The committee believes the sizing methodology used in the APS report is more realistic.[7] In addition, MDA canceled the Space Test Bed program in its 2010 budget. Moreover,

> in previous budgets, MDA had established the Space Test Bed to explore concepts for and to conduct research to support potential deployment of boost-phase intercept defenses in space. In the 2009 budget, MDA had planned to spend about $300 million for that research, and the Congressional Budget Office's (CBO's) projection of DOD's plans, based on the 2009 future years defense plan (FYDP), incorporated the assumption that an operational space based interceptor system would be developed and fielded.[8]

The SBI platforms would be placed in multiple rings of satellites, with multiple satellites per ring.[9] The orbits are inclined with respect to Earth's equator, and the maximum latitude that the SBIs can cover is a little larger than the inclination angle. Such a constellation of satellites

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[7] Op cit.

[8] Congressional Budget Office. 2004. *Alternatives for Boost-Phase Missile Defense*, Washington, D.C., July.

[9] The critical number for coverage is the average number of satellites within range, and that is well characterized by the product of the number of rings times the number of satellites per ring. The trade-off between the number of rings and the number of satellites per ring for a fixed product is slowly varying. In addition, the satellites were assumed to have a service life of about 7 years and the disposal of expired platforms is not taken into account.

results in nonuniform coverage of the ground, where "coverage" means the number of satellites that are within range to deliver an SBI to a threat missile within the time window. Generally speaking, one wants to have at least one SBI within range, but it may be desirable to have more than one for redundancy or to deal with raids. There is substantially better coverage (i.e., more satellites within range) for latitudes near the orbit inclination angle and poorer coverage at low latitudes. However, coverage at latitudes above the orbit inclination rapidly drops to zero above the latitude of the inclination of the orbit.

Airborne-Based Interceptors

Recently, ABIs, also known as airborne hit to kills (AHTKs), have been reconsidered and show some potential applications in certain conflict scenarios. The primary difficulty with ABIs, like all other proposed kinetic boost-phase systems, is the need to be close enough (within about 50 km) to the target so that an interceptor with a given speed and a KKV of sufficient agility can reach and successfully home in on the accelerating booster before the boost phase ends. ABI programs have existed in the past, but today only a few low-end ABI systems based on existing interceptors remain on the drawing boards—for example, the network-centric airborne defense element (NCADE), based on a modified advanced medium-range air-to-air missile (AMRAAM) missile, and the air-launched hit-to-kill (ALHK) program, based on an air-launched version of the PAC-3 missile. These systems might be able to intercept boosting targets at very short range, but they rely primarily on aerodynamic forces for divert and, consequently, cannot intercept accelerating targets above approximately 30 km in altitude, where most of the boost phase occurs, especially for missiles with ranges beyond 1,000 km. Hence, they cannot provide a robust boost-phase intercept capability.

ANALYSIS

Overview

A boost-phase defense system is one that presumably avoids the midcourse countermeasure problem, provided the system can intercept the hostile missile's burning booster rocket with its bright exhaust plume before the hostile missile reaches its desired velocity and deploys its payload. If such a boost-phase defense system can achieve that end within the extremely short engagement window available, it can protect a large area against launches from a specific locale. In principle, boost-phase intercept is technically feasible and appears attractive. To take an extreme example, a soldier with a 50-caliber machine gun or handheld rocket launcher 300 yards from a missile launch pad could easily destroy that missile as soon as it lifts off its launch pad. This is so for three reasons: (1) the soldier can see the hostile missile as soon as it emerges from its launcher; (2) the speed and acceleration of the hostile missile at that time are very low compared to the fly-out velocity of the soldier's firepower; and (3) the hostile missile's motion at that time is tracked by the soldier's eyes and is predictable. For the same reasons, an Aegis SM-2 Block IV antiair missile can shoot down a short-range ship-launched Scud-type theater missile during boost if the Aegis ship is downrange within 50 km of the launch.

Unfortunately, trying to intercept a hostile booster rocket (solid or liquid propellant) from a significant distance dramatically turns the tables. For one thing, there is not much time between knowledge of where the hostile missile is directed and the time available for the interceptor to reach out to hit the target at a militarily useful range. This is compounded by the fact that the hostile missile is traveling at about the same velocity as the interceptor and its acceleration is less predictable. Even so, it is possible to guide a suitably maneuverable interceptor in order to hit a hostile thrusting booster, assuming the interceptor can get there in time.

As noted in Chapter 1, the committee had access to classified information provided by the Missile Defense Agency on its programs of record; however, the committee chose to develop a set of notional threat missiles, notional interceptor designs and notional sensors to explore the basic physical limitations of missile defense system performance, with the understanding that a public report was not only requested by Congress but also helps improve public understanding of ballistic missile defense issues. The following analysis is based, in large part, on notional data developed by the committee and is stated as such throughout this chapter. While boost-phase defense has been advocated as the most efficient way to deal with fractionated payloads and exoatmospheric (midcourse) penetration aids, such systems are extremely vulnerable depending on threat booster characteristics and operational considerations. The committee's analysis of boost-phase defense concludes that it could be technically possible in some instances but operationally and economically impractical for almost all missions.

Time, Range, and Technical Constraints: Iran and North Korea as Examples

As previously noted, the committee's analysis focused on assessing U.S. boost-phase defense systems against ballistic missile threats from Iran and North Korea. Figure 2-3 illustrates the dilemma for all boost-phase defense systems (i.e., the pressing intercept timelines for both solid and liquid threat booster rockets) and specifically displays this dilemma for what most boost-phase defense advocates would call the less onerous of the two ballistic missile defense problems—that is, defense against ICBMs launched from North Korea). Moreover, advocates for boost-phase defense would argue that because of the North Korea's relatively small size and proximity to a coastal boundary, Aegis ships along with military aircraft could get fairly close to the threat boost trajectories in order to minimize the reach required. In Figure 2-3, it is assumed that the threat was detected at an altitude above the cloud cover, which we would assume to be 30 sec after launch of a notional solid-propellant missile and 45 sec after launch of a notional liquid-propellant missile.

In understanding the challenges of boost-phase defense of the U.S. homeland and Canada, it is helpful to begin by looking at the ground tracks of trajectories on the rotating Earth from launch to impact and where an ICBM payload lands as a function of where its boost is terminated. Figure 2-4 shows the ground tracks of ICBMs launched from Iran and North Korea to reach the United States.[10]

While it is convenient to describe missile performance in a standard way, that is, on a nonrotating Earth basis—it is important, particularly for longer range threats, to consider rotating Earth effects. This is important both for assessing what territory is at risk for a given threat missile performance and for looking at the ability to engage such threats during their boost or early midcourse phase of flight. While there are additional second-order Earth effects—such as Earth's oblateness (nonspherical shape) and local gravity variations—which must be considered in accurate targeting, these are not of importance for this discussion.

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[10] Figures 2-4 to 2-8 and Figures 2-11 to 2-16 were generated from the committee's analysis using Google Earth. ©2011 Google, Map Data©2011 Tele Atlas.

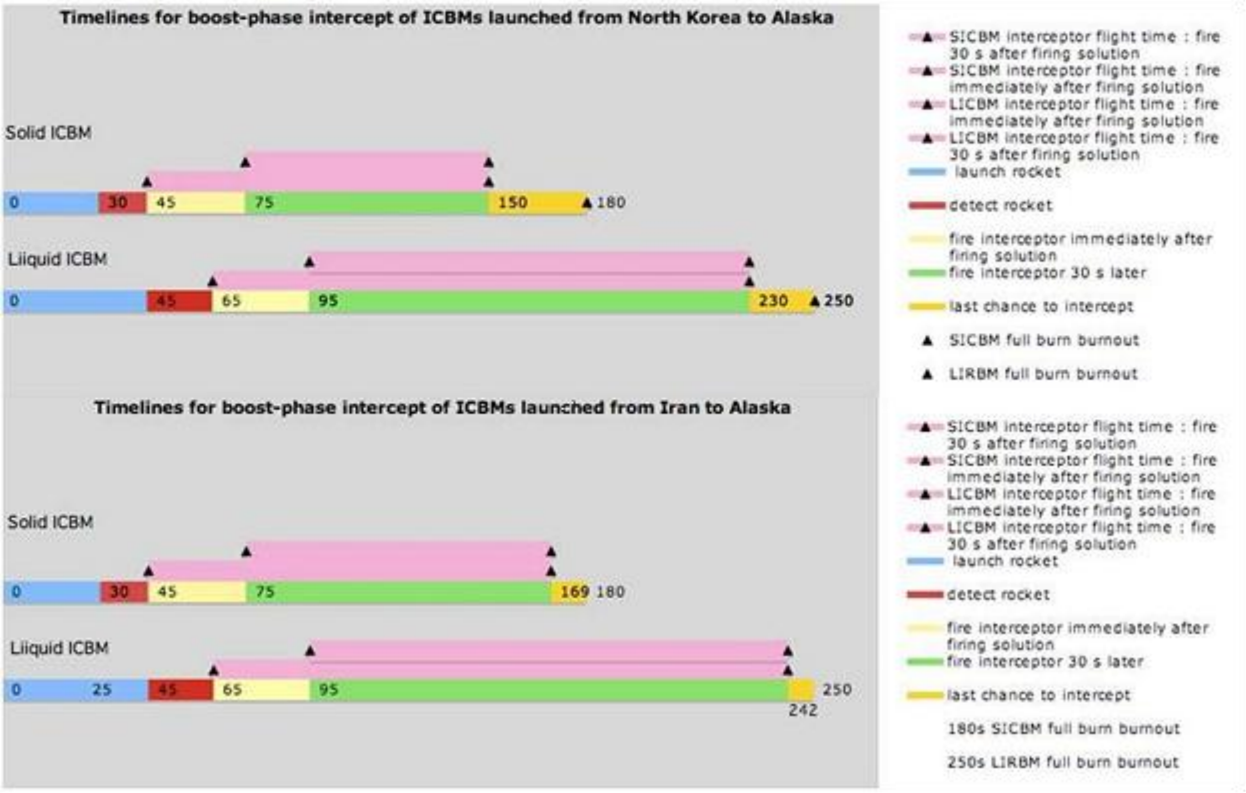

FIGURE 2-3 Timelines for ICBM boost-phase intercepts of ICBMs launched from North Korea (upper) and Iran (lower). Based on data from David K. Barton, Roger Falcone, Daniel Kleppner, Frederick K. Lamb, Ming K. Lau, Harvey L. Lynch, David Moncton, et al. 2004. *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues,* American Physical Society, College Park, Md., October 5, pp. S23 and S80.

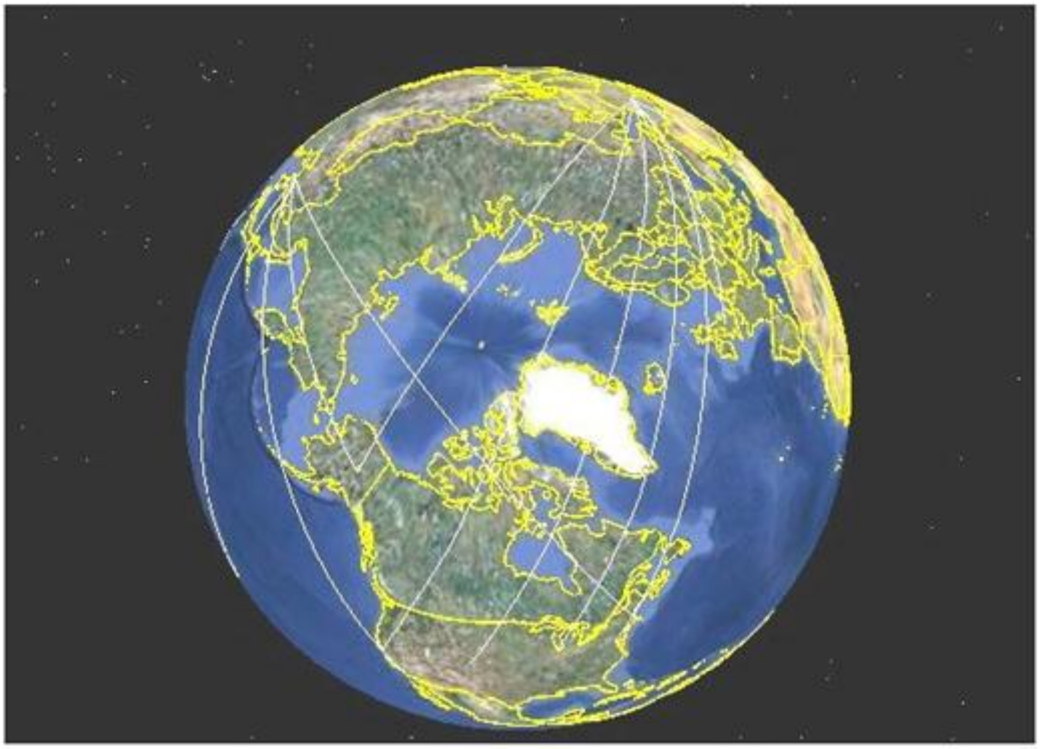

FIGURE 2-4 Notional trajectories for ICBMs launched from Iran and North Korea toward North America.

When a ballistic missile flies due north, the effect of Earth's rotation on range is small (2-3 percent), affected by the launch azimuth required to account for the initial missile velocity owing to Earth's tangential velocity at the launch point and also to lead the target, which moves during the flight time of the missile. When a missile is launched in an easterly direction, Earth's rotation increases the maximum range of the missile relative to its nonrotating Earth descriptor.

Conversely, when launched in a westerly direction, Earth's rotation reduces the reach of that same missile. Intuitively the opposite should be true since the target movement from west to east during the roughly 30-40 min flight time of the missile (~7.5 degrees of longitude, or ~800 km at the equator) would be the dominant effect. However, keeping in mind that an ICBM has a burnout velocity of 6.5-7.4 km/sec or so, Earth's tangential velocity at the launch point (almost 0.5 km/sec for a launch point at the equator) has a much greater effect on the effective range of the missile than the distance the target moves during the flight time.

For example, if a missile with a nonrotating Earth range of 12,000 km is launched from the center of Iran and flies almost due north, the actual ground range, including Earth rotation effects, is close to the range for a nonrotating Earth. Thus that missile is able to strike Seattle, approximately 12,000 km away. On the other hand, that same missile launched against the East Coast has a launch azimuth of about 315 degrees (45 degrees west of north), and that same missile can only reach a great circle range of about 10,000 km. To reach all of Florida or Texas at a great circle range of 12,000 km, a nonrotating range capability in excess of 14,000 km would be required.

These differences are important for three reasons. First, when the threat posed to the United States is assessed, the actual ground range reach is an indicator of an adversary's goals. Second, since the longest ground range needed determines the minimum energy trajectory for a given missile, a longer range with its lower flight path angle and altitude at boost termination as well as in midcourse flight, this range also determines the reach required for early intercept of an ICBM aimed at the United States or an IRBM aimed at northern Europe from a site in the Middle East (see Figure 2-4).

Third, Earth's rotation between the time of launch of the threat from any given point until the launch of an interceptor sited to counter that threat affects the trajectory of the interceptor needed for earliest and latest engagement of that threat as well as the footprint that can be defended. For the purposes of this study, the maximum range of a missile is the distance to which it can fly a given payload mass and constraints on its boost trajectory such as (1) the maximum dynamic pressure, which typically establishes the heating and thermal protection for structure and controllability requirements due to wind shears, and (2) the dynamic pressure at first-stage separation, which determines control requirements to recover from deviations in angle of attack due to first-stage-thrust tail-off.

Figure 2-5 shows contours of thrust cutoff time (with a total burn time of 250 sec) for a representative two-stage liquid ICBM with a maximum nonrotating Earth range of 12,000 km that is launched from the safest location in North Korea. Figure 2-6 then shows similar contours for a representative solid propellant ICBM of the same maximum range with a maximum burn time of 180 sec. Moreover, the analysis shows that a boost-phase defense system emplaced for protecting the western third of the United States and mainland Alaska would need to intercept a North Korean-launched ICBM that uses liquid propellant at about 230 sec (or 20 sec before burnout) and one that uses solid propellant at 150 sec (or 30 sec before burnout).

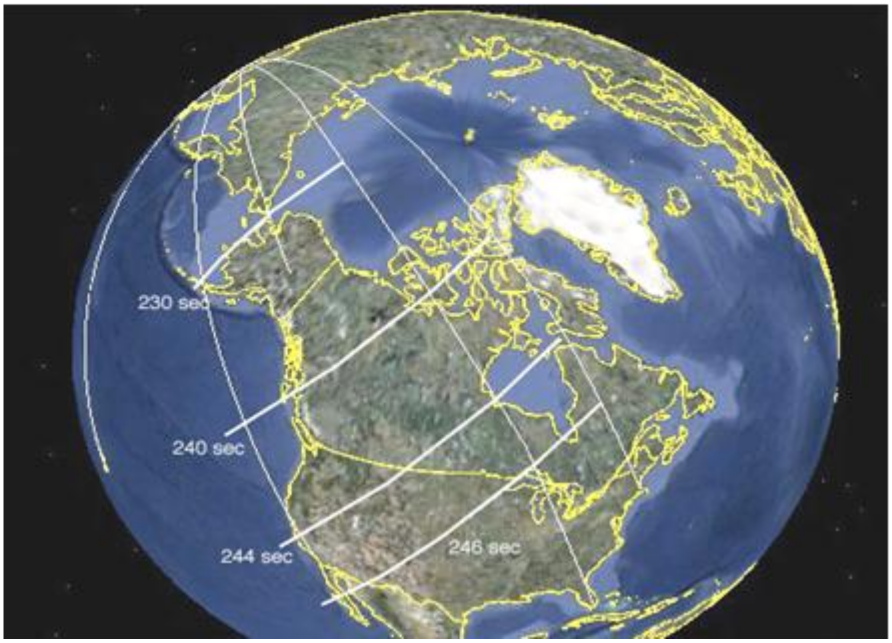

FIGURE 2-5 Thrust cutoff time contours for a notional two-stage liquid ICBM with an assumed total burn time of 250 sec and a maximum nonrotating Earth range of 12,000launched from North Korea.

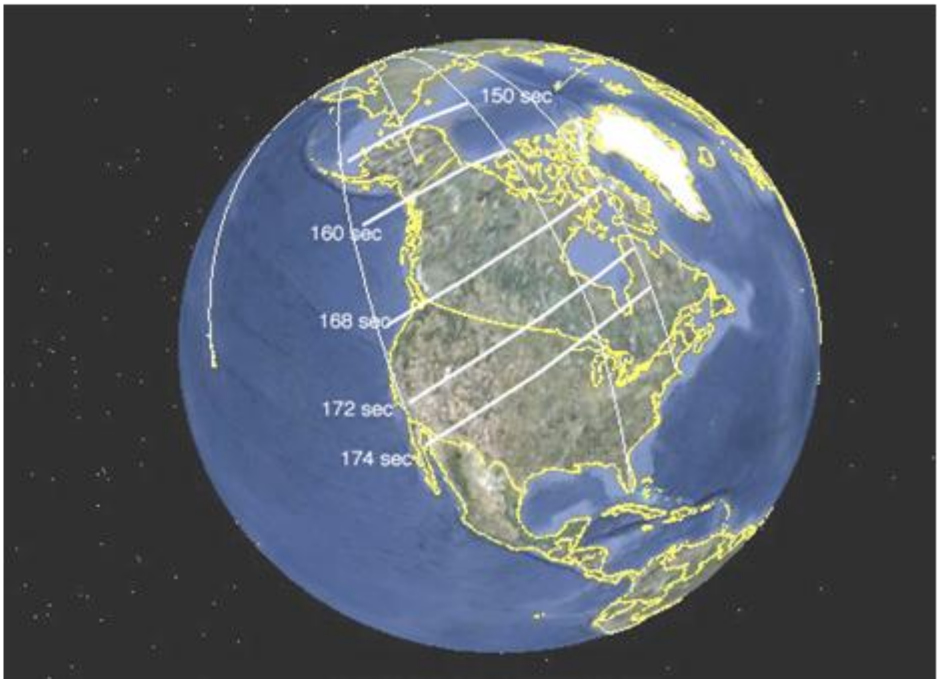

FIGURE 2-6 Thrust cutoff time contours for a notional three-stage solid ICBM with an assumed burn time of 180 sec and a maximum nonrotating Earth range of 12,000 km launched from North Korea.

A similar analysis is provided for Iran. Specifically, Figures 2-7 and 2-8 show similar contours for ICBMs launched from central Iran; however, the ICBM range must be more than 13,300 km because the missiles, particularly those targeting the East Coast of the United States, would be launched in a northwesterly direction and their reach would be reduced by the effects of Earth rotation. In summary, the analysis shows that a boost-phase defense system emplaced for protecting Alaska is the most stressing case and would need to intercept an Iranian-launched ICBM using liquid propellant at about 242 sec (or 8 sec before burnout) and one using solid propellant at 169 sec (or 11 sec before burnout) for the notional ICBM designed used in this study.

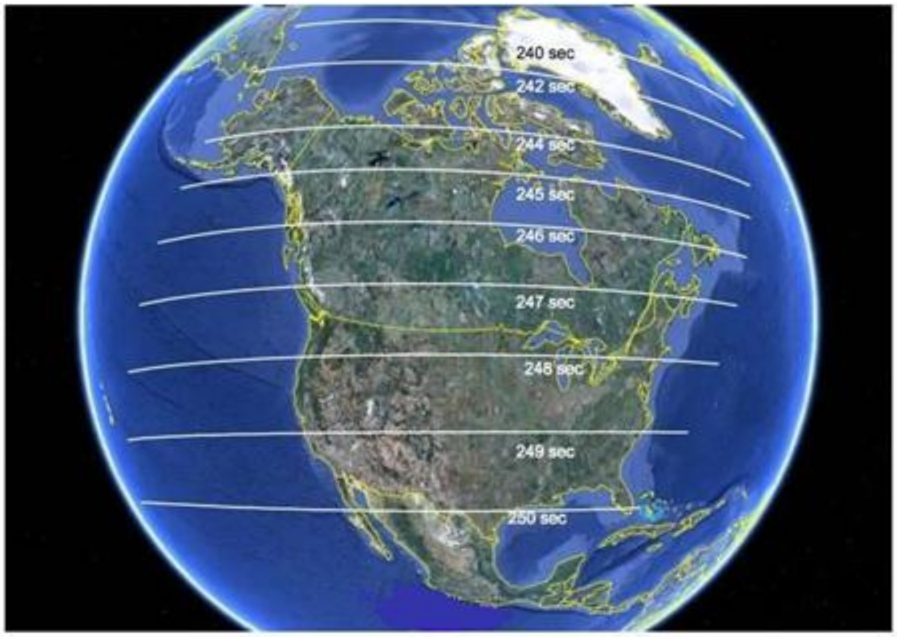

FIGURE 2-7 Thrust cutoff time contours for a notional two-stage liquid ICBM with a maximum nonrotating Earth range of 13,300 km that is launched from central Iran.

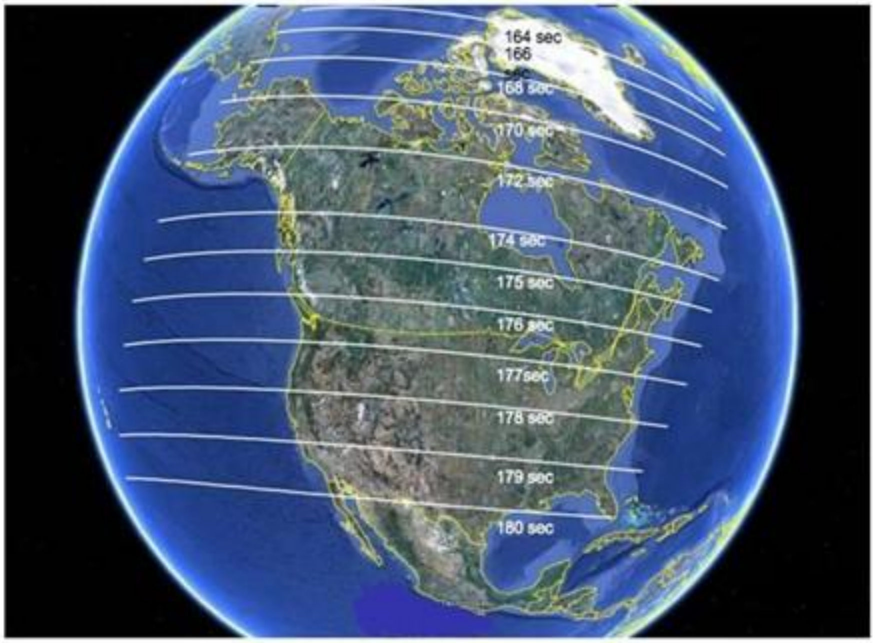

FIGURE 2-8 Thrust cutoff time contours for a notional three-stage solid ICBM with an assumed burn time of 180 sec and a maximum nonrotating Earth range of 13,300 km launched from central Iran.

Up to this point, the analysis has shown the pressing time constraints for achieving boost-phase intercept against a notional ICBM—solid or liquid propellant—launched from Iran or North Korea toward the United States (including Alaska) and Canada. Now, the reach of any given interceptor is calculated. To assess terrestrial-based kinetic boost-phase defense, the committee chose two sizes of interceptor. The first was a notional 6 km/sec fly-out velocity, 70-sec burn interceptor without a third stage.

The second was a notional 4.5 km/sec fly-out velocity interceptor that could be carried in the vertical launch system (VLS) Aegis system. It also could be carried and launched by a tactical aircraft. These two interceptors, carrying a KV with the necessary agility for the boost-phase missions, were used to understand engagement performance for both Iran and North Korea.

Figure 2-9 shows how the reach of the interceptor is calculated.[11] Here, head-on (coplaner) engagements define the maximum reach that an interceptor of a given fly-out velocity launched at the earliest opportunity would have to kinetically engage the hostile missile at the desired time. This maximum reach, R, applies to any interceptor launched within a circle with radius R, derived from a projection of the desired intercept point on the ground track. Figure 2-10 shows an example of a coplanar, or head-on, engagement for the notional 6 km/sec interceptor against a North Korean liquid ICBM that was modeled and then used like the preceding construction example to determine the general case of engagement at any aspect angle.[12] The interceptor fly-out contour times are referenced to the detection at an altitude of 7.5 km plus 15 sec in accordance with the timeline in Figure 2-3 to allow the missile to develop enough horizontal velocity so the sensor can select a rough point at which to commit an interceptor without a high risk of wasting it by exceeding its divert capability during boost. The range from interceptor launch point is shown to be about 515 km for intercept at a time after launch from North Korea, consistent with avoiding impacts on North America.

Using planar engagement simulations like the one shown in Figure 2-9, it is possible to calculate the greatest distance (or reach, R) to the earliest point at which a kinetic interceptor with a given fly-out velocity could engage a hostile missile. A view over the North Korean launch point in Figure 2-11 shows the azimuth and boost ground tracks to various parts of the United States (noted at the top of the figure) for notional liquid- and solid-propellant ICBM threats from North Korea. One can see where intercepts must occur geographically in order to defend North America against such threats.

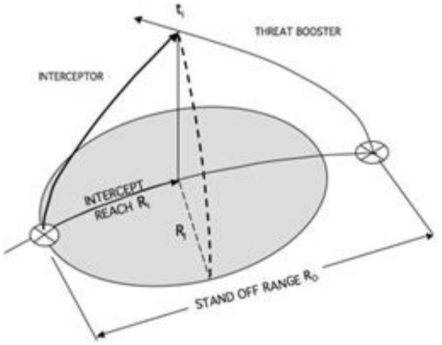

FIGURE 2-9 The boost-phase engagement—calculating reach of the interceptor. SOURCE: Based on data from David K. Barton, Roger Falcone, Daniel Kleppner, Frederick K. Lamb, Ming K. Lau, Harvey L. Lynch, David Moncton, et al., 2004, *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues,* American Physical Society, College Park, Md., October 5.

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[11] See David K. Barton, Roger Falcone, Daniel Kleppner, Frederick K. Lamb, Ming K. Lau, Harvey L. Lynch, David Moncton, et al, 2004, *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues,* American Physical Society, College Park, Md., October 5.

[12] The boost-phase intercept problem is dominated by the challenge of the short burntime of solid fuel rockets. However, North Korea currently uses slower burning liquid fuels. Since the North Korean threat has been the focus of much U.S. homeland defense work, this constrained threat is worth analysis. It must, however, be kept in mind that North Korea could shift to solid fuel, possibly with external assistance, in an effort to frustrate U.S. defenses.

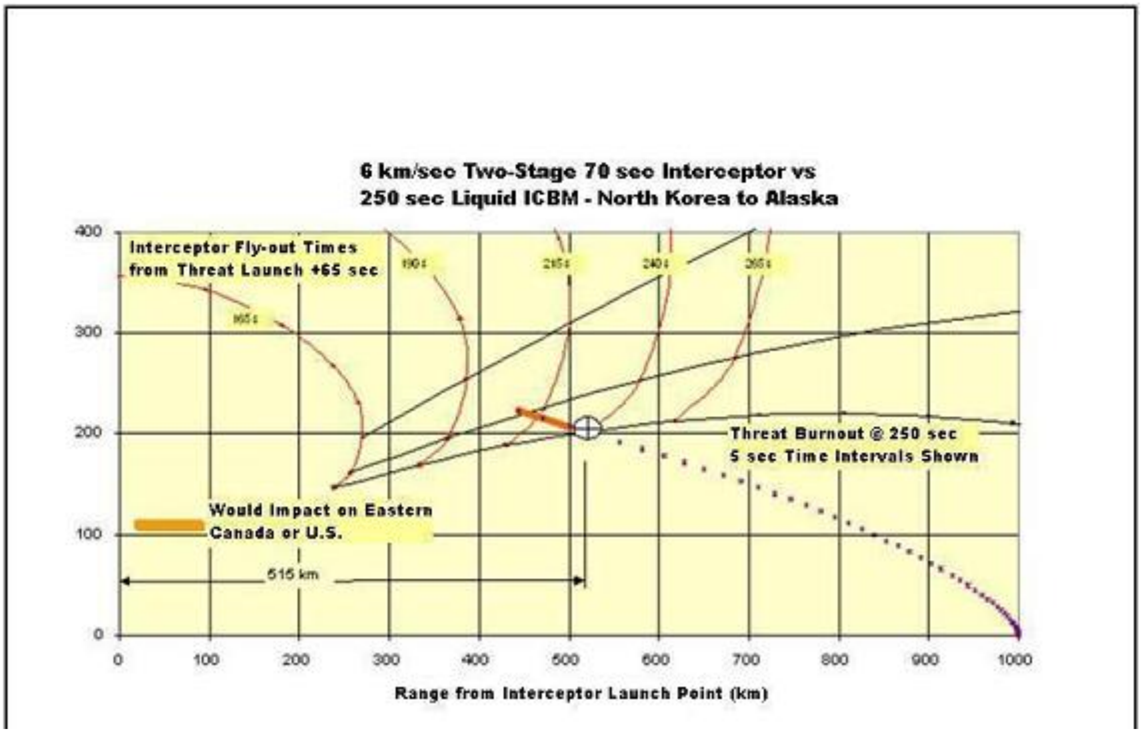


FIGURE 2-10 Fly-out fan for a notional 6 km/sec interceptor engaging a liquid-propellant ICBM head-on to determine R.

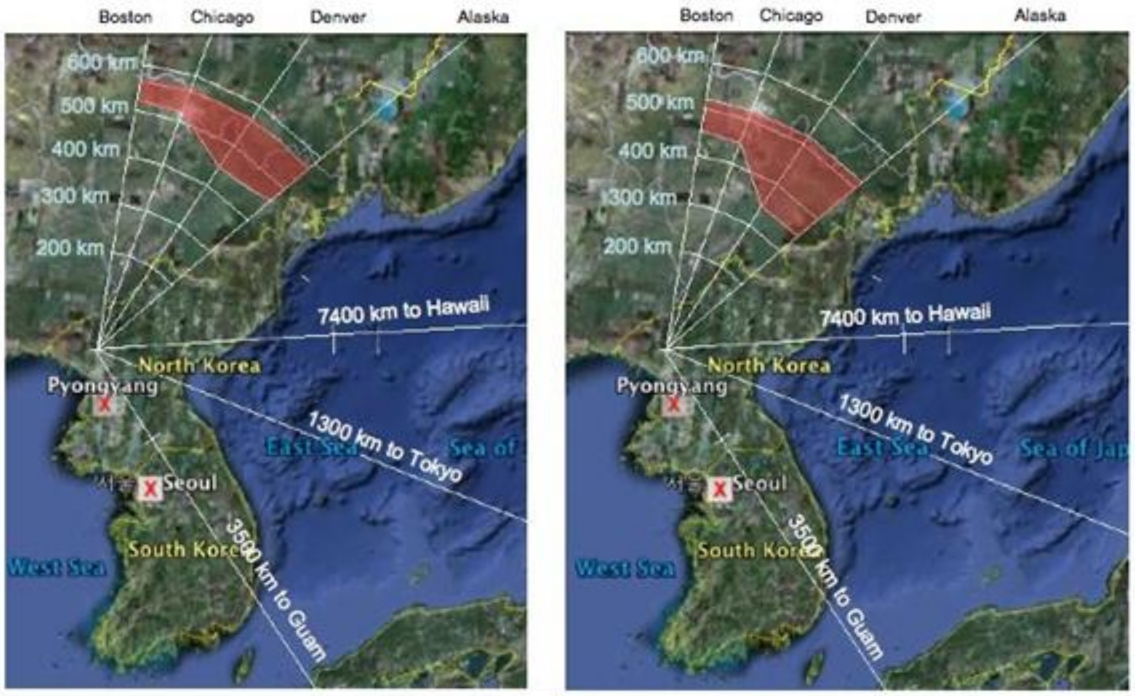


FIGURE 2-11 Illustrative boost-phase ground tracks for notional ICBMs to various parts of the United States from North Korea: (a) notional liquid ICBM and (b) notional solid ICBM.

The red region is the ground range where threat boost termination would result in impacts in the United States and Canada. It applies to all boost-phase intercepts regardless of basing. The northern edge of the red zone is where the burnout for maximum range occurs. The southern edge is the cutoff times derived from the impact contour charts. Ground range from the launch site is shown for reference. The solid threat burns out at 519 km from its launch point, and the liquid threat burns out about 575 km from the launch point. The launch point was chosen to maximize the difficulty of both intercepts and attacks on the launch site for their adversaries. The more easterly fly-outs show the need for earliest intercept of ICBM threats to Alaska. Also shown for reference are ground tracks and ranges to Hawaii, Tokyo, and Guam.

Land-, Sea-, or Air-Based Kinetic Boost-Phase Defense

The committee first examines the requirements and limits for terrestrial-based boost-phase interceptors. In all cases, these interceptors are constrained by geography and sovereignty to basing that is militarily and politically viable. Figure 2-12 shows where these same boost-phase defense systems would need to be emplaced in order to kinetically engage liquid-propellant ICBMs aimed at America; Figure 2-13 shows this information for solid-propellant ICBMs.

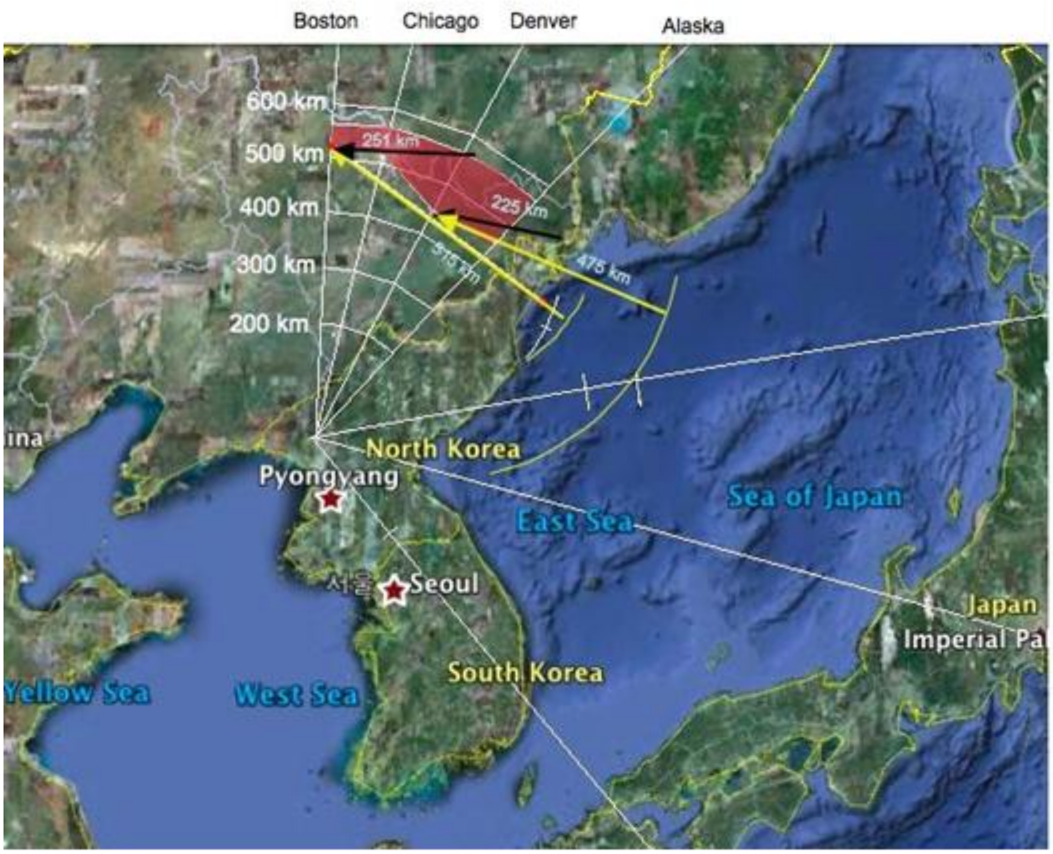


FIGURE 2-12 Notional interceptor ranges to kinetically engage a liquid-propellant ICBM launched from North Korea. Yellow and black arrows represent fly-out velocities of notional 6 km/sec and 4.5 km/sec interceptors, respectively.

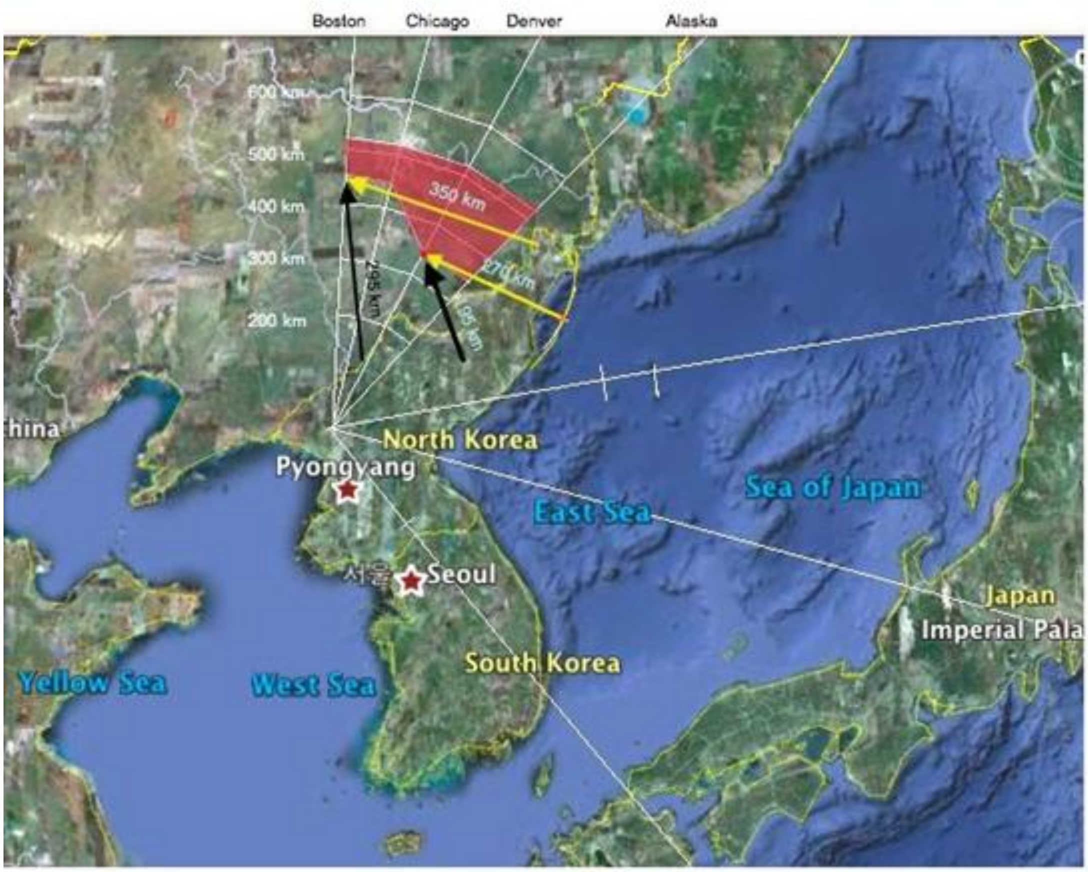


FIGURE 2-13 Notional interceptor ranges to kinetically engage a solid-propellant ICBM launched from North Korea. Yellow and black arrows represent fly-out velocities of notional 6 km/sec and 4.5 km/sec interceptors, respectively.

In both Figures 2-12 and 2-13, the launch point for the notional ICBMs launched from North Korea was chosen to make intercepts and attacks on the launch site the most difficult—that is to say, the safest locations, as shown in Figures 2-11. Figure 2-12 shows the radius of the arcs within which notional interceptors with fly-out velocities of 4.5 km/sec (shown as black arrows) and 6 km/sec (shown as yellow arrows) must be based in order to intercept before the red zone is reached. It can be seen that even with no decision time, (1) no 4.5 km/sec terrestrial interceptor can engage in boost-phase intercept even against slow-burning liquid ICBMs unless it is launched from China or North Korea itself and (2) the 6 km/sec interceptor, if based on a ship, can engage the more easterly liquid ICBM trajectories, but to engage the more western trajectories headed to eastern North America it would have to be so close to the North Korean coast as to be highly vulnerable to attack.

Engaging notional solid-propellant threats from North Korea is even more constrained, as shown in Figure 2-13. Reaching even the more easterly notional threat trajectories requires a 6 km/sec interceptor to be based unacceptably close to the adversary’s territory. Note that the reach of the 4.5 km/sec interceptor is greater against notional solid ICBMs than against liquid ICBMs even though solid burn times are much shorter. This is because the notional liquid boost trajectories are of lower altitude and the 4.5 km/sec interceptor cannot get low enough at longer range to engage the notional liquid-propellant threat at a greater distance.

Because of their shorter burn times and lower burnout altitudes, it is not feasible to intercept notional short- and medium-range missiles with ground- or sea-based versions of the two interceptors or space-based interceptors in the exoatmosphere. Intercepting notional missiles of 2,000 km range or less during boost would require interceptors that can engage within the atmosphere, and those interceptors would have to be close to the threat launch point. One such example is a notional 1,300 km single-stage missile aimed at Tokyo. Here, boost-phase intercept of such an attack is infeasible with a platform outside North Korea's airspace.

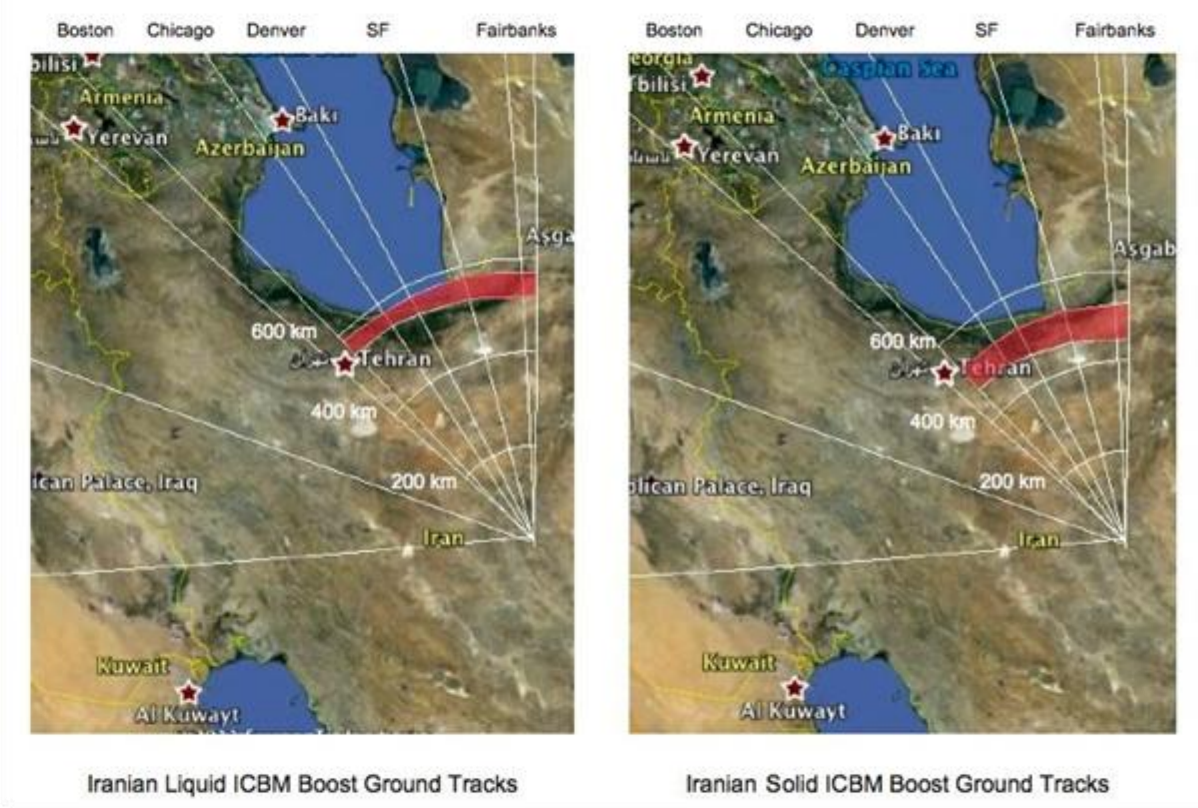
The committee found only one case of a notional ICBM launched from North Korea against Hawaii that could be engaged during boost phase by a notional 4.5 km/sec interceptor, provided it has a more agile KV than currently planned.

In summary, Figure 2-12 shows that a notional North Korean-launched liquid-propellant ICBM aimed at the east coast would be the most pressing challenge for a boost-phase defense system to kinetically engage. Moreover, a ground-based boost-phase interceptor with a nominal speed of 6 km/sec would have to be based at sea or in China to reach the boost phase of a notional North Korean liquid-propellant ICBM. However, a notional 6 km/sec interceptor appears to be too large to be carried in the Aegis vertical launch system (VLS) or on a tactical aircraft. From Figure 2-13 it is evident that a notional 4.5 km/sec interceptor has no viable boost-phase capability against a notional solid ICBM unless it overflies North Korean airspace and that even a notional 6.0 km/sec interceptor, when sea based, has little room to maneuver, and then for only a limited azimuth of threat launches.

One can conclude then that, until otherwise demonstrated, no airborne or Aegis VLS-based interceptor could be used for boost-phase defense against notional ICBMs aimed at the United States, even against a country that is as small as North Korea and that is accessible by sea, unless those interceptors are based on or over neighboring territory or over the threat country itself. However, a possible application limited by the interceptor fly-out envelope and on-station endurance is the engagement of notional longer range missiles launched from North Korea against Hawaii or other Pacific Ocean targets where the boost trajectories are headed toward international waters or allied territories and where boost-phase interceptors can be stationed.

A similar analysis is provided for notional ICBMs launched from Iran and aimed at North America. Figure 2-14 shows the fly-out ground tracks and azimuths for notional liquid- and solid-propellant ICBMs launched toward North America from central Iran. The launch location is assumed to be central Iran. As with North Korea the red zone is the zone in which a velocity has been reached that would allow impacting the area being defended. Threats must be engaged in their boost phase before reaching that zone regardless of where the interceptor is based. Also shown are ranges and azimuths to Israel and Gibraltar.

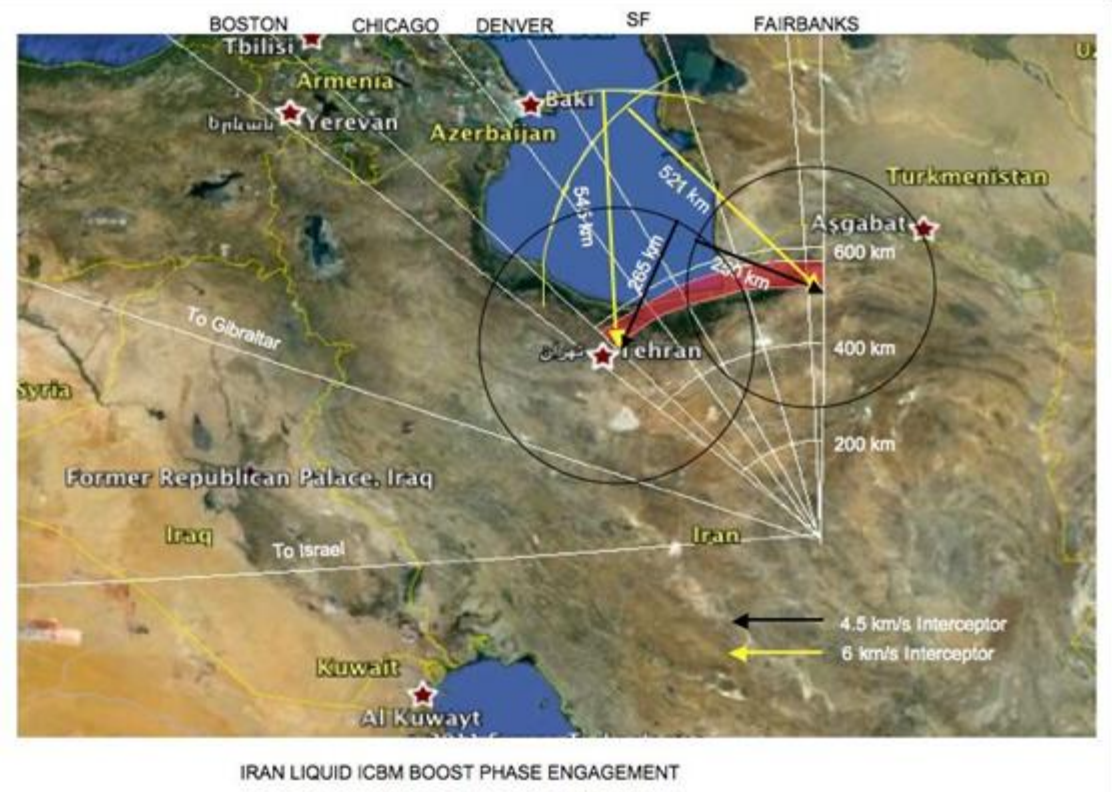
Figures 2-15 and 2-16 illustrate the problem of engaging notional long-range ballistic missiles launched from Iran (Figure 2-15 is for liquid-propellant ICBMs whereas Figure 2-16 is for solid-propellant ICBMs). Again, the black arcs represent the reach for a notional 4.5 km/sec interceptor against a notional liquid ICBM. No matter whether the ICBM is headed to North America, as shown, or to Europe, a 4.5 km/sec interceptor would have to be based in the Caspian Sea or in neighboring territory in Turkmenistant to be able to catch liquid ICBMs in their boost phase. Even a notional 6 km/sec interceptor would have to be in the Caspian Sea or in neighboring territory in Azerbaijan or Turkmenistan. No effective boost-phase defense of Europe or the Middle East is possible because of the shorter burn times associated with medium and intermediate-range ballistic missiles and the fact that Iran could arrange to launch the attack from locations such that no boost-phase interceptor could be in range from outside Iranian airspace. There has been some discussion of the use of stealthy aircraft or UAVs carrying interceptors loitering in the southern Caspian; however, because of the limited reach of airborne boost phase interceptors and the fact that even stealthy airborne platforms could potentially be vulnerable to air defenses, such concepts seem impractical at the current time.



Iranian Liquid ICBM Boost Ground Tracks

Iranian Solid ICBM Boost Ground Tracks

FIGURE 2-14 Fly-out ground tracks and azimuths for notional liquid and solid ICBMs launched toward North America from central Iran.



IRAN LIQUID ICBM BOOST PHASE ENGAGEMENT

FIGURE 2-15 Notional boost-phase engagement of liquid ICBMs launched from Iran.

FIGURE 2-16 Notional boost-phase engagement of solid ICBMs launched from Iran.

For notional solid ICBMs launched from Iran the possible basing area shrinks even more for the notional 6 km/sec interceptor, but the reach of the notional 4.5 km/sec interceptors actually increases somewhat. While this is counterintuitive, it is so because in this case, the trajectory of a liquid ICBM in its boost phase is significantly lower than that of a solid ICBM such that the interceptor cannot launch until it can engage at an altitude it can enforce. Accordingly, with one or two exceptions, terrestrial-based boost-phase defense systems do not appear attractive given the timeline and geopolitical constraints.

Directed-Energy Boost-Phase Defense

The range and time constraints on boost-phase defense using kinetic intercept is one reason for the interest in the use of directed-energy weapons for boost-phase defense.[13] The ABL was designed to exploit the delivery of energy at the speed of light to perform the boost-phase intercept mission. Space-based lasers have also been pursued. Virtually no fly-out time is involved, although dwell time on target is involved, and the beam agility is a function only of how fast the pointing optics can be repositioned. While laser weapons sound like the obvious answer, the irradiance (power per unit area) that a laser can deliver on a distant target is ultimately limited by the power of the laser and the diameter of the exit optics of the device. In reality, atmospheric effects will substantially disturb the propagation of the beam to a degree that increases rapidly with the distance traveled through the atmosphere. Much has been accomplished, however, in developing pointing and tracking capabilities and AO to maintain beam quality.

While laser energy is transmitted at the speed of light, the damage mechanism for continuous wave lasers is the heating of materials to failure, which requires a certain dwell time.

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[13] Additional information and analysis can be found in the classified annex (Appendix J).

The amount of energy delivered per unit time is determined by the energy density of the prime energy source and by the limits on the size and weight of the hardware to convert that primary energy into a beam and project it. These limit the practical power, aperture, and endurance of lasers that can be carried on real platforms.

In the end, even though laser propagation is nearly instantaneous, the dwell time to heat the target is substantial and, depending on the target material and coupling efficiency, takes several seconds, even in the absence of countermeasures to harden the booster against laser attack. With countermeasures, the challenge is greater. Raid missile launches stress the ABL. In the CONOPS there would be at best two ABLs flying in a single combat air patrol (CAP) within range of the missiles, and each ABL can engage only one threat at a time. There is a limited window of opportunity to effect intercepts in which the missile is high enough to have a thin enough air column in the laser's path for long-range propagation and before the threat burns out. In short, the ABL has a limited number of shots without refueling the laser. The slewing from one target to another can be done in a relatively short time.

There are other limits to the useful range of high-energy lasers for boost-phase engagements. Even at the speed of light and the relatively thin atmosphere at the operating altitude of the ABL, atmospheric effects degrade the coherence of the beam unless variations in the structure of the atmospheric path from the laser to the target are compensated for in real time. This requires leading the target, and, even at the speed of light, the round trip of the calibration beam limits the effective range.

When a laser such as the ABL (now renamed the airborne laser test bed (ALTB)) is based on an aircraft, it is propagated through the atmosphere over a substantial distance, albeit at lower densities than propagation on the ground. Thus the properties of the atmosphere vis-à-vis the laser wavelength are very important. These properties include the absorption, scattering, and turbulence. Those wavelengths that are strongly absorbed by the constituents of the atmosphere are inappropriate for long-distance propagation. Notably, these are the wavelengths absorbed by atmospheric water vapor, carbon dioxide, carbon monoxide, oxides of nitrogen, and so forth, and they are ruled out. Fortunately, there are several windows in the atmospheric transmission where absorption is small enough to allow radiation to be propagated over hundreds of kilometers. The early lasers, starting with the carbon dioxide, hydrogen fluoride/deuterium fluoride (HF/DF), and COIL lasers, were chosen because their wavelengths were in such low-loss atmospheric windows.[14]

While the exact design power cannot be provided in this unclassified report, MDA describes the ABL as a multimegawatt laser and the ALTB as a megawatt-class laser. By the early part of 2010, the ALTB HEL had achieved about 80 percent of the Tail 1 design power. This performance can be improved, but substantial effort would be required.[15] This does not appear to be a high priority at this time for MDA, and correctly so.

Inhomogeneities in the density of the atmosphere, called "turbulence" for short, result in inhomogeneities in the index of refraction. In turn, these variations perturb the propagation of a laser beam. A beam that would have been focused in a uniform atmosphere will no longer be focused. This is a problem well known to astronomers who use ground-based telescopes. The best solution for astronomers is to avoid the atmosphere and have the telescope in space—as, for instance, the Hubble Space Telescope—eliminating the problem. In the same way a laser weapon would be space based. For operation in the atmosphere, one would try to minimize the distance the beam travels through the atmosphere. Thus, a high flying aircraft is a much better

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[14] Additional information on the ABL/ALTB, including wavelength selection, is provided in the classified annex (see Appendix I).

[15] Missile Defense Agency. 2010. "ALTB Questions in Preparation for March 16-18 Presentations to the National Academy of Sciences," March 17.

platform than a device on the ground. There is a practical limitation on the altitude at which a very massive laser may be flown and kept aloft for many hours at a time. This limit is about 12 km for the 747-400F airframe and the load that it must carry.

Minimizing the atmosphere is not sufficient, however, and other measures are required. Astronomers have used AO to at least partially cancel out atmospheric disturbances, achieving great improvements in imaging. These phase distortions can be applied using a deformable mirror, but there are limitations on how well this works.

It is convenient to distinguish between two classes of AO errors and corrections: (1) first order and (2) higher order. These describe the variation of the phase error across the aperture. First-order (i.e., linear) errors cause an apparent movement of the whole image with time as the atmosphere changes, because the phase error is linear across the aperture. This is a prism distortion. Left uncorrected, the object is not positioned where it appears to be. Because of the time variation, this blurs the image over the time of exposure. Usually, the first-order error is the most serious. It can be compensated for by a simple, flat mirror that tips or tilts, keeping the image in the same place. Second-order (quadratic) and higher errors are defocus and two types of astigmatism. They are corrected using a deformable mirror whose local shape can be varied in compensation. These corrections are also time dependent. The higher order corrections are much more complex, but also important.

The ABL makes its AO corrections using two different systems. To make a first-order correction, the nose of the target missile is illuminated with a TILL and the edges of the nose image are used to define the position of the target. The TILL is a kilowatt-class solid-state laser that instead of being focused on the target, illuminates it with a meters-wide beam to see the geometrical edges. In turn, the first-order phase distortion derived from the nose image is applied to a planar mirror for the HEL beam to correct this error. To deal with higher order errors, a second kilowatt-class laser (BILL) provides a beacon on the body of the target. The wavefront of this image is processed, and the phase corrections are applied to a deformable mirror to correct the HEL beam.

For various reasons, one of which was the ABM Treaty, the ABL was designed for use against short-range theater missiles, not long-range missiles like ICBMs. Because the long-range missiles burn longer and burn out at higher altitudes, more of the optical path goes through less of the turbulent atmosphere. Consequently, the AO problem is much easier to solve. In turn, this means that the effective range of the ABL can be greater for long-range missiles than for short-range missiles.

In principle an advantage of the ABL is that aircraft could be deployed to respond to an evolving threat. This could be simpler than deploying an entire ground-based interceptor base. However, the redeployment of an ABL CAP would require enough aircraft to maintain an aircraft on station at the previous threat area(s). In addition, ABLs require substantial infrastructure on the ground for supply and maintenance. Thus, such a redeployment is by no means trivial.

The original plan for the ABL program called for two developmental aircraft, one of which, known as Tail 1, exists. A second development aircraft, designated Tail 2, was planned. Both Tail 1 and Tail 2 were intended as research tools, not as operational weapons. It was anticipated that once the development was complete, a fleet of seven operational aircraft would be acquired for a single CAP. This would allow the ABL to be used for boost-phase defense at one site.

The Air Combat Command (ACC) CONOPS document for the defense against one threat location (within the coverage of a figure-eight flight pattern) would require seven aircraft.[16] Of

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[16] DOD Office of Testing and Evaluation. 2010. "Airborne Laser (ABL) Assessment of Operational Effectiveness, Suitability, and Survivability," January.

the seven, five would be needed to keep two aircraft on station 24/7, and two would be in maintenance. If the maintenance has not included any laser or chemical operations, the aircraft can be rapidly turned around for another sortie until ~23 hr of engine run time accumulates, at which point engine oil servicing is required. If there have been laser or chemical operations, 24 hr are required between sorties.[17] A standard crew shift would normally be limited to 12 hr to avoid fatigue. A single fuel load can keep the aircraft aloft for 7 hr at about 12 km. Without refueling, 1 hr of that time would be for transit from base to station, 5 hr on station, and 1 hr to return to base. With refueling, there would be one refueling during a single crew shift. A report from ODT&E notes that refueling time is about 1 hr, so the total time on station would be 12 – 1 – 1 – 1, or 9 hr for a 12-hr mission.[18] From this, it is easy to see that at least five flight-ready aircraft would be needed to keep two on orbit with redundancy to cover some gaps.

Clearly it would be very important to establish air supremacy over the enemy territory where the ABLs would fly. The ABLs are very high-value assets, and they would be high-priority targets for an enemy attack. MDA has suggested that the ABLs could fly with escort aircraft to deal with conventional aircraft.[19] The committee does not concur with this suggestion. The long-term escort of unarmed assets is not supported by Air Force policy. MDA has also suggested that the ABLs have some self-defense capability, but the committee has not been told how that function would fit into the CONOPS. There is an obvious vulnerability, because the laser weapons cannot defend the rear of the aircraft.

A different and more challenging threat to the ABLs would be long-range SAMs. Simply staying out of range of SAMs may prevent an ABL from attacking an enemy's missile. The use of onboard self-defense systems similar to those on other operational aircraft has been suggested, but the committee has no information on the efficacy of such measures for this application.[20] The ABL's weapons are not well suited for attacking an incoming SAM, and they would offer no defense at all for an attack beyond the field of regard of the turret for the rear 120 degrees of azimuth. Ideally, establishing air supremacy would include taking out all the air defenses like SAMs.

Establishing air supremacy before the outbreak of hostilities would be very provocative and could itself lead directly to hostilities. Thus, it is more likely that the ABL would be used only after hostilities had begun, and that it would therefore be of limited value in stopping the first attack from an enemy.

Space-Based Boost-Phase Defense[21]

Space-based boost-phase defense can avoid the geographic limitations of terrestrial systems and can in principle engage even ICBMs from a large country. However, it would require hundreds and perhaps several thousand interceptors stored in orbit and would be more than 10 times as expensive than any other defense alternative.

Because geography is a fundamental constraint on terrestrial-based boost-phase defenses, advocates for space-based boost-phase intercept argue that putting the interceptors on orbiting satellites eliminates that constraint. On the other hand, a spaced-based system would face two other daunting constraints. Like all other proposed boost-phase defense systems, they must get from their orbital bases to the threat missile just as fast, with the same very short decision times,

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[17] Missile Defense Agency. 2010. "ALTB Questions in Preparation for March 16-18 Presentations to the National Academy of Sciences," March 17.

[18] DOD Office of Testing and Evaluation. 2010. "Airborne Laser (ABL) Assessment of Operational Effectiveness, Suitability, and Survivability," January.

[19] Missile Defense Agency. 2010. "ALTB Questions in Preparation for March 16-18 Presentations to the National Academy of Sciences," March 17.

[20] Ibid.

[21] Additional information and analysis can be found in the classified annex (Appendix J).

and to be close enough to do. If the interceptors are to be constantly in a position to intercept, many platforms would be needed that must obey the laws of orbital mechanics. In addition it would be very expensive to put them into orbit and sustain them there in the first place.

Figure 2-17 illustrates how SBIs fly out from their storage orbit to engage ascending missiles during their boost. The SBI circles Earth in its storage orbit at some velocity and altitude. When dispatched to intercept a missile during boost, the SBI fires, adding more velocity to reach the threat. Since that fly-out velocity can be added in any direction with high Like a terrestrial-based boost-phase interceptor, until detected and tracked long enough to know in which direction it is roughly headed, an SBI cannot be flown out from its storage bus or garage on orbit. While space-based interceptors do not have to deal with flying out through atmospheric drag, and therefore for similar fly-out velocities can be smaller, they have to be boosted into orbit along with their host vehicle or garage. There is therefore a very great sensitivity to each kilogram of mass in the space-based interceptor, particularly in the kill stage. Specifically, after being boosted into orbit, the kill stage must be flown out from the orbiting garage at high acceleration and greater velocity in order to maximize its reach in the optimum-sized constellation. The result is a need for hundreds of SBIs to handle just the relatively slow liquid-propellant threats, and 2,000 or more to have a shot at the faster solid-propellant threats during their boost. Constellation sizing trades are discussed next.

Nations like North Korea and Iran lie between 25 and 42 degrees north latitude. Missiles fired from those countries toward the United States will burn out several hundred kilometers further north. So, the number of satellites required in the constellation is that number needed to always have at least one (and preferably two) close enough to reach a booster after it is launched—in all cases before booster burnout but (like all other boost-phase intercepts) before it

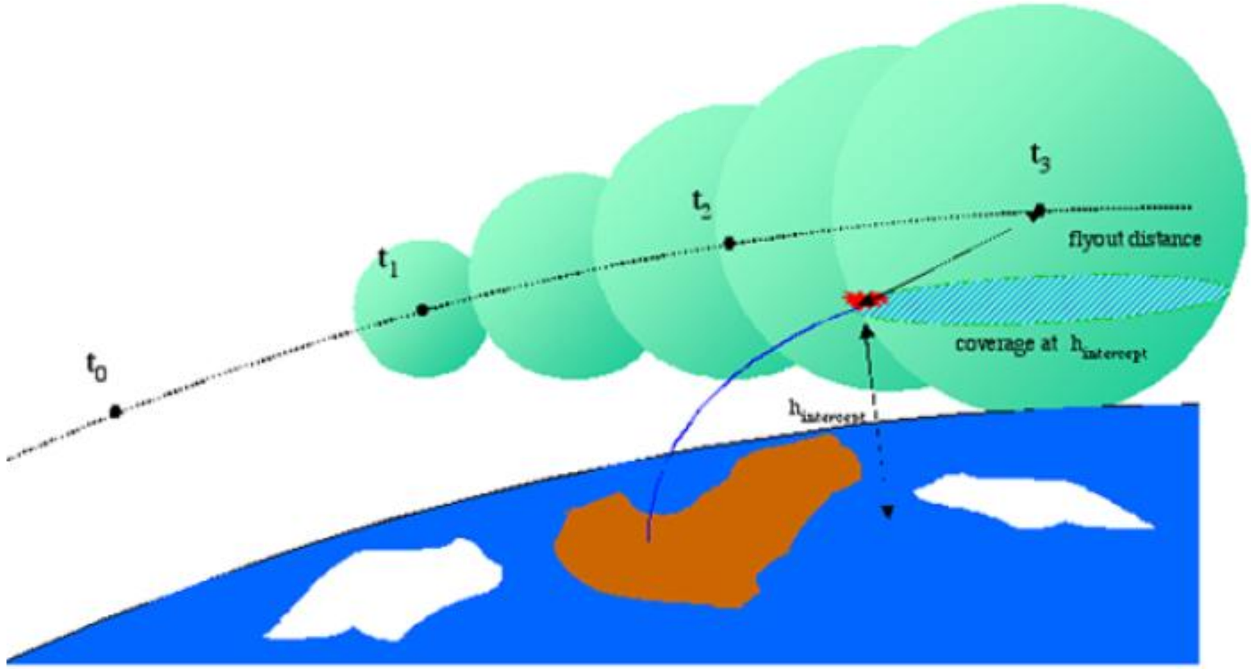

FIGURE 2-17 Area and volume coverage from orbit of space-based interceptors. SOURCE: Adapted from Figure 4.12 in David K. Barton, Roger Falcone, Daniel Kleppner, Frederick K. Lamb, Ming K. Lau, Harvey L. Lynch, David Moncton, et al., 2004, *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues*, American Physical Society, College Park, Md., October 5, p. S60.

reaches the velocity that would hit an area one wants to avoid—certainly Canadian or U.S. territory and, probably also, Russian or Chinese territory.

The laws of orbital mechanics mean that the minimum number of space-based interceptors must be in inclined orbits of at least 45 degrees. The population of SBIs is determined once again by the fly-out speed of the orbital interceptor and the time available, taking decision time into account, for the orbital interceptor to get from its storage orbit to the threat at its fly-out speed. This in turn defines the so-called absentee ratio—that is, the total number of interceptors required to be orbiting Earth every 90 min or so to assure that at least one is close enough to engage a single threat missile launched at any time. Even if it is assumed that North Korea would deploy only slow liquid-fueled missiles like those that it currently uses, several hundred satellites would be required in the constellation to have a reasonable probability of engaging a single threat missile. If and when these countries apply the solid rocket technology that Iran is pursuing—a natural response to such a defense deployment—several thousand interceptors would need to be maintained in orbit.

Figures 2-18 and 2-19 show the probability that one or more satellites are within range $P(\geq 1)$ and the probability that two or more satellites are within range $P(\geq 2)$ as a function of the number of satellites in the constellation (N_{sat}). The probabilities are shown for decision times of 0 and 30 sec, and for notional 5.0 km/sec interceptors. The upper figure is for solid-propellant ICBMs and the lower figure is for liquid-propellant ICBMs. The assumed threats are for ICBMs launched from Iran. These cases are more stressing than launches from North Korea, even though the timeline is longer, because the greater concentration of satellites at the higher latitude of North Korea improves the coverage. The lead time for a country like North Korea to develop solid-propellant missiles is likely to be shorter than the time to develop and deploy a space-based defense system, which would probably be obsolete before it is deployed. Figure 2-20, created from a Monte Carlo simulation, illustrates what a space-based constellation of 1,600 satellites would look like, although even this constellation is not quite large enough to handle both liquid- and solid-propellant ICBM threats. The cost of a system capable of protecting against a single launch at a time is prohibitive. Consider, then, what would be required to deal with a simultaneous salvo of threat launches, a tactic that both North Korea and Iran have been practicing. Unless the constellation is populated sufficiently to handle salvos, there will be much leakage.

Potential Scenarios for Intercepting Hostile Missiles in the Boost Phase of Flight

One can envision scenarios in which intercepting hostile missiles in their boost phase of flight appears practical. Here are three such scenarios; however, it is important to note that none of the scenarios involves developing new systems such as ABL or KEI. Rather, each uses existing systems.

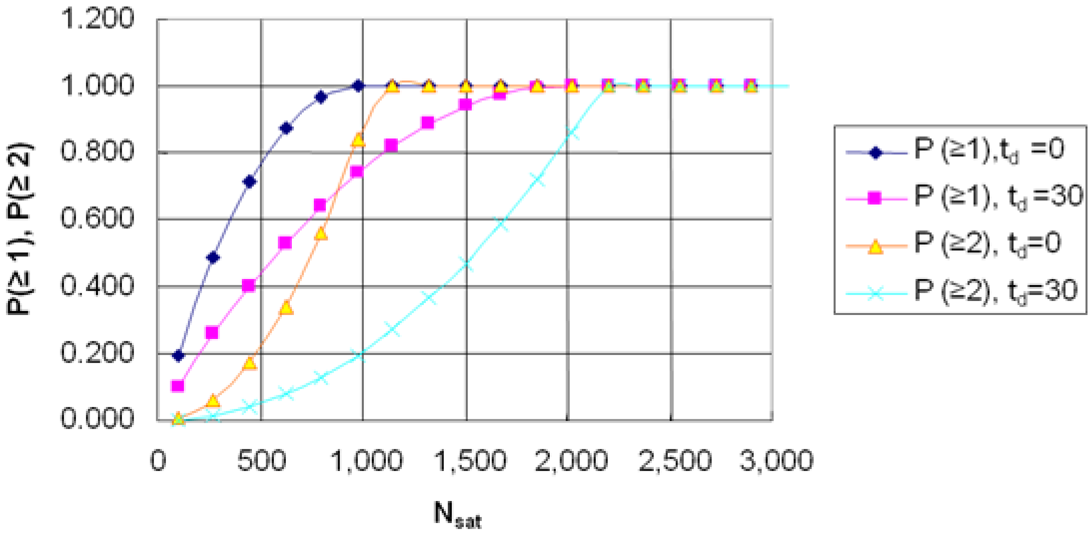

FIGURE 2-18 Probability as a function of the number of satellites in the constellation for a solid-propellant ICBM launched from Iran and notional 5.0 km/sec interceptors.

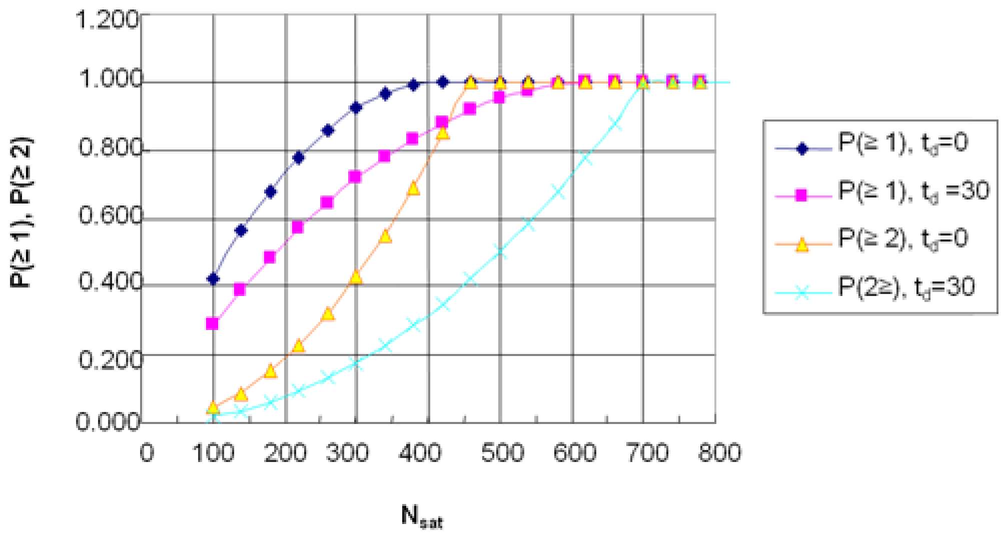

FIGURE 2-19 Probability as a function of the number of satellites in the constellation for a liquid-propellant ICBM launched from Iran and notional 5.0 km/sec interceptors.

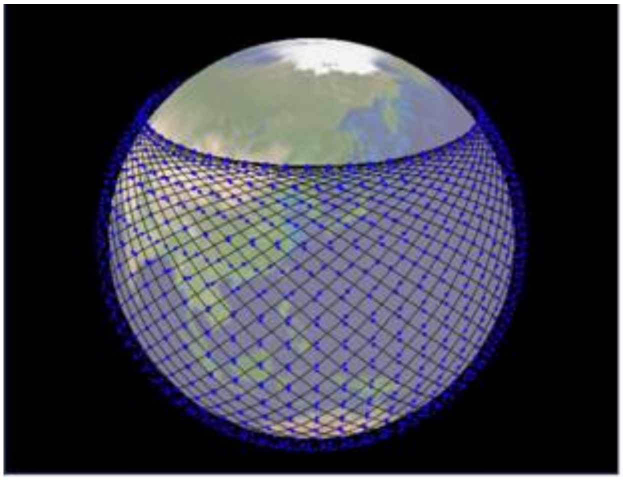

FIGURE 2-20 The approximately 1,600 satellites that must be maintained in orbit for a space-based boost-phase system to counter the solid rocket technology being pursued by Iran. ©2011 Google, Map Data©2011 Tele Atlas.

Countering Early Deployment of Chemical or Biological Submunitions in Theater Conflicts

Chemical or biological submunitions deployed immediately after boost phase are a low-technology threat that could saturate terminal and exoatmospheric defenses at shorter missile ranges. Because such weapons are area dispersed and do not require precise delivery, it is not far fetched to contemplate that if each is encapsulated in an ablative material such as silicone rubber to survive reentry, they could be deployed immediately after boost phase. While not a game changer on the battlefield, such weapons require the donning of protective gear, which would impede and disrupt combat operations. Such weapons are far more disruptive to civilian targets. The latter threat has been studied and found practicable when the short-range reentry heating is modest and the means for thermal protection does not need to be sophisticated. In such a case, the submunitions cannot carry and do not require individual guidance and control systems but simply are ejected at low dispersal velocity.

Only boost-phase intercept, prelaunch attack, or midcourse sterilization of the threat volume would be able to counter this type of threat. It is one scenario in which intercepting a hostile missile in its boost phase of flight might be efficacious. Specifically, carried by multimission aircraft as part of their ordnance load and having as their primary mission the destruction of a missile launch capability or other ground target, such airborne boost-phase interceptors could, once air superiority had been established, engage any weapons that were able to launch in an adversary’s airspace. Alternatively, some form of volume kill—sweeping or sterilizing the threat volume after the payload has been deployed—might be used. The sooner this could be done after submunition dispersal, the smaller the volume that would have to be swept but the more vulnerable the sweeper platform would be. Unfortunately, there is no effective volume kill capability other than the detonation of a nuclear weapon.

Countering Ship-Based Theater Ballistic Missiles Launched with Early Deployed Submunitions Against CONUS, Deployed Forces, U.S. Allies, Partners, or Host Nations

Some observers consider the possibility of attacks by short-range ballistic missiles launched from ships near U.S. (or allied) shores to be a very serious potential threat. Transfers of older liquid-fueled theater ballistic missiles (TBMs) to nonstate actors have already been reported. Ship-launched TBMs with chemical or biological submunition payloads from rogue or nonstate actors aimed at large U.S. coastal population centers would have no immediate return address. While the prospect of a nonstate actor getting nuclear material (at least enough for a dirty bomb) cannot be excluded, a simpler chemical or biological attack could do substantial damage and might be an attractive option for such an actor.

Because the launch point for such a threat would, by definition, be relatively close to U.S. territory, boost-phase intercept could be practical. Existing SM-2 Block IV air defense interceptors launched from within 50 km of the ship launching the threat could engage such shorter range threats during boost phase, within the atmosphere. In addition, CONUS-based tactical aircraft carrying weapons if developed for theater boost-phase intercept could be scrambled to fly CAP either over any suspicious ship that evaded detection before reaching a threatening range or until an Aegis ship arrived. For example, a fighter aircraft interceptor platform equipped with an appropriate acquisition sensor and perhaps a modified AMRAAM could be first on the scene for that mission if no Aegis ship was within 50 km.

These are not likely to be large-scale threats that warrant the development of a special system to counter them, and modified existing assets could probably play that defensive role at least for the coastal threat. Specifically, Aegis ships with some SM-2 Block IV interceptors that can shadow suspect ships closely enough to engage any launch in its boost phase, followed by a counterbattery strike on the ship itself, could be deployed on both coasts.

Countering Long-Range Missiles Launched from North Korea Toward Hawaii or the Mid-Pacific

There is a case in which the relative geographical location of a threat country and its potential target would allow boost-phase interceptors to be stationed routinely in positions from which boost-phase intercept would be feasible. This case is the long-range threat trajectory from North Korea to Hawaii or other mid-Pacific islands.[22] Here, three conditions would need to be met for such a boost-phase intercept to occur: (1) the threat would be coming toward the interceptor launch platform (an Aegis ship in international waters, say) so the geometry is at a favorable angle; (2) the boost-phase timelines would be long enough to allow a boost-phase engagement in that unique geometry; and (3) an SM-3 sized interceptor would have sufficient reach within a rational timeline, it would be externally cued, and its KV would have the necessary additional agility.

It has been suggested by some that a capability exists for the essentially instantaneous detection of a missile launch from its silo or launch pad, which would allow earlier commit of a boost-phase interceptor and thereby somewhat extend its range. Of course, very early detection would buy many seconds more of additional fly-out time for interceptors than would waiting for sensor data (from a space-based infrared system (SBIRS)). Here, the idea would be to fire an interceptor toward a nominal point in the fly-out corridor as soon as a launch is detected and to update the interceptor during its powered flight, when better data are available, diverting it to a better-predicted intercept point—with an intervening coast, if needed—before igniting a third stage. Boost-phase engagement firing doctrine calls for the interceptor to be used this way to divert during its powered flight in order to reduce the divert velocity and acceleration requirement for the kill vehicle to deal with; however, it does not commit interceptors until the threat's heading can be estimated.[23]

Testing of Boost-Phase Defense Systems: Results to Date and Outlook

The committee was tasked to assess the past and planned test programs' value in demonstrating feasibility and the cost effective utility of the KEI and ABL programs. While the

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[22] The "long range" condition reflects that some potentially significant targets, like U.S. bases on Guam or the Japanese homeland, are so close to North Korea that a ballistic missile aimed at them would have too short a burn time (and too low a burnout altitude) for a boost-phase intercept to be feasible from an Aegis inteceptor on board a ship in the Sea of Japan.

[23] The committee also shows that it is counterproductive to commit an intercept earlier than the timelines shown in Figure 2-3 even if the launch can be detected immediately (see classified annex, Appendix H).

cancellation of KEI and the realignment of the ABL program to an R&D test bed (with which decisions the committee concurs) have made this assessment somewhat moot, the committee has observations about both.

Kinetic Energy Interceptor

The KEI program was terminated after cost and schedule problems delayed flight testing of the vehicle. Both stages of the booster had been ground tested and were deemed ready for flight test, and simulations using some actual tactical warning and attack (TWAA) elements were conducted with the battle management architecture.

That said, the committee believes the foregoing analysis illustrates that no matter how successful tests might one day have been, the system would have had negligible utility as a boost-phase system because it cannot be based close enough to adversaries' fly-out corridors to engage either long- or short-range missiles without being vulnerable to attack. Neither KEI nor any version of SM-3 that will fit on existing launchers has enough reach to have military utility as a boost-phase defense.

The committee agrees with the decision to cancel the KEI program as such, but the booster rocket motors could, with some modifications, be used as part of a more effective Ground-Based Missile Defense (GMD) system. The committee returns to this subject—a recommended evolution of the GMD—in Chapter 5 of this report.

Airborne Laser

Several tests have been conducted with mixed results for one reason or another. None of the problems have been fundamental to successful operation of the laser or its beam conditioning and control. Several target missiles have been destroyed, but all the tests have been at ranges too short to have any military utility for boost-phase defense. The limitations of the ABL are due to the need to sight at low elevation angles through the atmosphere, which fundamentally limits the standoff range for boost-phase engagements. No amount of future testing is likely to change that limitation.

Accordingly, the committee concurs with the DOD Office of Testing and Evaluation (OT&E) report, which concludes that the ABL has no operational utility for missile defense for a variety of reasons, not the least of which is the illogic of placing such an expensive asset in harm's way because of that range limitation.[24] The committee found no reason to believe that ABL could ever be an effective boost-phase defense system, and it believes that the reversion of the ABL to a research and development test bed was a sound decision.

There are logical applications that were identified by the Defense Science Board in an unclassified report that do not entail such short reaction times, going in harm's way, endurance on station, or atmospheric problems at low elevation angles.[25] Specifically, the single existing ABL could serve as an emergency antisatellite (ASAT) device. The aircraft could on its own timeline be positioned to deposit energy on a spacecraft for dwell times limited only by its entire operating time at very high angles of elevation without going anywhere near an adversary's air defenses. Advanced high-powered solid-state or hybrid lasers could be tested on board as well.

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[24] DOD Office of Testing and Evaluation. 2010. "Airborne Laser (ABL) Assessment of Operational Effectiveness, Suitability, and Survivability," January.

[25] Defense Science Board. 2001. *Defense Science Board Task Force on High Energy Laser Weapon Applications*. Office of Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., June.

FINDINGS

Terrestrial-Based Boost-Phase Defense

Major Finding 1: While technically possible in principle, boost-phase missile defense—whether kinetic or directed energy, and whether based on land, sea, air, or in space—is not practical or feasible for any of the missions that the committee was asked to consider. This is due to the impracticalities associated with space-based boost-phase missile defense (addressed in Major Finding 2), along with geographical limits on where terrestrial (nonspace) interceptors would have to be placed and the timeline within which such interceptors must function in order to defend the intended targets.

- Intercept must take place not just before burnout of the threat booster but before it reaches a velocity that can threaten any area to be protected. Because of the short burn times of even long-range ballistic missile boosters, the interceptor launch platform cannot for its own survivability be so close to the territory of an adversary as to be vulnerable to the adversary's perimeter defenses, but it must be close enough to the boost trajectory so that the interceptor can reach the threat missile before it reaches its desired velocity.
- Surface-based boost-phase interceptors are not feasible against a large country like Iran for missiles of any kind unless the interceptor platforms are based in the southern Caspian Sea. While it has been suggested that unmanned stealthy aircraft could loiter inside or close to the borders of an adversary, the committee does not believe it to be a feasible approach against a country with an effective air defense like Russian S-300 SAMs, in the face of which stealth aircraft will have a limited time of invulnerability as they maintain station in an environment with a high-density air defense sensor.

Range Limits

In practice, the operational limits on both kinetic and laser interceptor ranges necessitate that boost-phase defense platforms be located near likely launch sites (or, more precisely, near possible intercept points). Locations that meet the requirements are available only in certain limited circumstances—a relatively small threat nation and good access to areas near it over international waters or friendly territory and outside the range of its air defenses.

For kinetic interceptors, range is limited by the short duration of powered flight for ballistic missiles—approximately 180-250 sec for ICBMs (although some liquid-fueled types may have longer boost times) and approximately 60-180 sec for short-, medium-, and intermediate-range ballistic missiles.

Boost-phase defense of allies or deployed forces against shorter than intercontinental range attacks requires even closer stationing than for longer range threats, because shorter boost times and lower altitudes at burnout—which are the determinants of the windows for boost-phase intercept and of the proximity requirement for both kinetic and laser intercept—are even more demanding. Only in highly favorable geographic situations, e.g., trajectories from North Korea to Hawaii and some other Pacific Ocean targets, is it likely that boost-phase interceptor platforms could be located so as to overcome the time, distance, and altitude constraints.

Despite their essentially unlimited speed of "flight," the use of lasers as the kill mechanism does not avoid the requirement for relatively close-in stationing of the interceptor platform. Lasers operate at the speed of light, but they are range limited because laser power deteriorates with distance from the target. Moreover, although the laser beam reaches the target at the speed of light, it must dwell on the target for several seconds to deposit sufficient energy on the booster to destroy it. The altitude of the target at thrust termination and of the platform for the interceptor also contribute to loss of power on the target, limiting effective ABL range. The dwell time relative to the short duration of an engagement also limits the raid handling capability of any laser ballistic missile defense system.

The net effect of these time, altitude, and range constraints is that both kinetic and laser boost-phase interceptors must be ready to engage from within a few hundred kilometers of the intercept point. As a practical matter, the interceptor platforms must be ready to engage on or over international waters or friendly land areas. (It is sometimes claimed that stealth UAVs armed with boost-phase interceptors could operate in an adversary's air space. However stealth is extremely difficult to maintain for platforms loitering for long periods in airspace under surveillance by a reasonably capable air defense.)

Decision Time and Command and Control

Missile defense operates within the established military chain of command and employs systems of control and authorization that are consistent with standard operational practices that have withstood the test of time and suit real-world considerations.

In standard U.S. practice, weapons release authority is reserved for the higher command echelons, indeed ultimately for the President as commander in chief of the armed forces. Reliable and redundant communication links tie the release authority to the personnel in immediate control of the weapons system in question. However, it is equally a principle of the command and control system that requirements for higher-level authorization should not be so inflexible as to delay action to the point of ineffectiveness. Rules of engagement—which can change as threat conditions change—are guidelines for action, including when time or other considerations make seeking higher authority infeasible.

The special circumstances of missile defense—the potential of a missile attack to do massive damage, the ramifications of mistakenly destroying a foreign nation's space launch vehicle (or even a routine developmental test missile), the possibility of creating space debris (or debris or even weapons falling to Earth), the compressed timelines and heavy reliance on sensor data—make it difficult to strike the appropriate balance between higher level—ultimately Presidential—control and sufficiently rapid response.

These problems arise for any missile defense. The flight time for an ICBM attacking the United States from Iran would be only about 40 minutes, and all other flight times can be shorter. The time needed to detect and characterize a threatening launch—probably on the order of 1 min—and the time needed to conduct the intercept after weapon release—on the order of 15-17 min for midcourse intercept—leave a window of only a few minutes for requesting release authority, for the decision maker to consider and make the decision, and for that decision to be communicated to personnel who control the interceptor system.

The problem is challenging enough for midcourse intercept, where the window for engagement would be a few tens of minutes. Even more daunting would be the authorization of a boost-phase intercept, for which there would be virtually no time because the interceptor would have to begin the engagement within seconds of the sensors reporting that a hostile launch had occurred.

The short boost period not only imposes limits (far more significant for kinetic than for laser kill systems) on the time available for the intercept itself, it also means—for either laser or kinetic kill—that there be very rapid detection of the launch; its classification as threatening; tracking; decision and release authority to engage; and execution of release with all of these in addition to whatever time is needed for the engagement itself. Accomplishing this in the time available is a formidable operational challenge.

The short time for intercept raises an important policy question. To allow boost-phase interceptors to be fired within a few tens of seconds of detection of the launch of the attacking missiles, authority to engage would have to be delegated to the military personnel with immediate control of the system. Indeed, in practice, the "decision" to intercept would need to be made largely by a computer program, with human input essentially limited to confirming that the system appears to be functioning properly. Accordingly, civilian and higher level military authority would have to be exercised by determining the rules of engagement that were embodied in the computer program rather than in real time during an actual attack.

Other Issues

A significant technical limitation of boost-phase intercept, in addition to those presented by the short powered flight of the target, arises from the fact that ballistic missiles are accelerating nonuniformly during powered flight, not to mention almost discontinuously at staging events. This further complicates predicting the target's future location, which for kinetic-kill intercepts increases the divert requirements for the kinetic-kill vehicle. Also, the target is accelerating rapidly, which means that the interceptor must have a comparable acceleration capability. As a result, kinetic kill vehicles designed for midcourse intercepts will have limited boost phase intercept capability even if one assumes they are stationed within range of the intercept point. These requirements for boost-phase kinetic kill can be met technically, but they add to the weight and complexity of boost-phase intercept systems.

A further technical and operational issue for boost-phase intercepts is that even a successful intercept has the "shortfall" problem—that is, the potential not just for fragments of engines, fuel tanks, and the like but also for an intact and armed nuclear weapon to fall on friendly or neutral territory. Moreover, it is a misconception that a boost-phase intercept could cause threat missile debris to fall on the country of origin. In short, it is physically impossible for this to happen unless the interceptor is based in the country of origin and is close enough to the threat launch point to intercept the threat in the atmosphere.

Indeed, by the time of intercept, which would take place relatively late in powered flight and well above the atmosphere, the reentry vehicle (RV) would already have been given sufficient velocity to continue on a trajectory that could extend into the original target area, or at least into friendly or neutral territory, and produce a nuclear detonation on impact. In principle, a kinetic-kill boost-phase interceptor could be aimed so as to impact the RV containing the warhead (as contrasted to the booster itself), but ensuring such impact would be challenging, because of uncertainties about the position of the RV relative to the hot rocket exhaust, which is guiding the interceptor. A laser kill mechanism, even if properly aimed, would probably not be powerful enough to destroy a warhead carried on an RV hardened to survive reentry. It might, however, be possible to count on midcourse defense to deal with RVs that "escape" from a boost-phase intercept. It can therefore also be concluded that none of these measures to mitigate "shortfall" are likely to be effective, and that the consequences of a nuclear detonation on land "caused" by a U.S. intercept would be so severe that a boost-phase system must constrain intercepts to windows that minimize the risk of an RV falling on land. Such a constraint would, however, add another significant limitation to the already extremely tight window for intercept.

Finally, boost-phase intercepts are not immune from countermeasures, including hardening to reduce the booster's vulnerability to lasers, spoofing precursor launches, and the like. Iran has conducted tests in which several missiles of various types were launched nearly simultaneously. A nation could seek to defeat a boost-phase defense by launching several decoy boosters at the same time as the actual missile in the hope of confusing, or even overwhelming, the defense's sensors and data processors. Even more sophisticated countermeasures can be postulated—for example, fractionated upper stages—though typically they come at a price to the offense in terms of complexity and reduction in volume available for the weapons payload.[26]

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[26] Additional discussion on decoys and countermeasures is provided in the classified annex (Appendix J).

Overall Evaluation

As a practical matter, however, these other potential disadvantages would be dwarfed by the fact that both kinetic and laser interceptors would have to be on platforms relatively close to the targets. Even leaving aside how such proximity would expose the interceptor platforms to attack, this range-determined constraint makes boost-phase intercept operationally infeasible, because, except in a few cases, it would not be realistic to count on a boost-phase intercept platform being close enough to effect intercept.

- In particular, Iran is too large geographically (and its northern neighbors too unlikely to consent to U.S. boost-phase intercept overflights or basing) to make boost-phase operationally feasible, even against liquid-propellant ICBMs.
- By contrast to Iran, the small size of North Korea and its long coastlines mean that boost-phase intercept for ICBMs is not ruled out by geography, as long as North Korea sticks to liquid-propellant engines, and a large enough interceptor such as KEI could be based at sea, as explained below.
- In general, boost-phase intercept systems are more feasible the longer the boost time of the target missile. Therefore, they tend to be more feasible against liquid-propellant missiles than solid-propellant missiles, owing to the longer boost times associated with the former. However, it would be imprudent to justify boost-phase intercept development based on its potential against liquid-propellant missiles when solid-propellant missiles are an obvious countermeasure; such a system could become obsolete as soon as it is deployed. In fact, the deployment of a boost-phase intercept system would likely stimulate the development of solid-propellant systems if they were not already being pursued for other reasons (e.g., solid-propellant missiles are more suitable for mobile deployment and hence can survive better against air attack). For example, Iran already has tested a two-stage solid-propellant medium-range ballistic missile (MRBM). Boost-phase intercept deployment against liquid-propellant missiles would be justified only if a hostile country does not, or cannot, deploy solid-propellant ICBM technology, as was the case for the former Soviet Union for almost 40 years. So far, there is no sign that North Korea is working on solid-propellant rockets for longer range missiles, but it could shift toward solid propellant, possibly with assistance from Iran, with which it has significant cooperation. The question becomes, Should the United States invest in a boost-phase system with some capability against liquid-fuel North Korean ICBMs if that country might shift to solid-fuel rockets before or soon after the system becomes operational?
- There may be specialized cases in which boost-phase defense is feasible because either the threat must come toward the platforms or the platforms can be placed close enough to the threat and in an adequately benign environment. For example, a boost-phase intercept might be workable if the threat is North Korean medium- or long-range missiles heading toward U.S. bases in the western Pacific and therefore flying toward the Sea of Japan, on or over which boost-phase intercept platforms could be stationed. In this situation, and comparable situations elsewhere, the platform proximity problem is manageable, because the threat is coming toward the interceptor.

Space-Based Boost-Phase Defense

Major Finding 2: While space basing for boost-phase defense would in principle solve the problems of geographical limits that make surface-based boost-phase intercept impractical, the size and cost of such a constellation system is extremely high and very sensitive to the timeline in which interceptors must be launched. As a result it is susceptible to countermeasures such as salvo launches that either delay and reduce its coverage or squander space-based intercepts.

- In principle, a constellation of satellites equipped with boost-phase interceptors could be configured so as always to be geographically in range for an intercept. The number of satellites required depends, in part, on the burn time and altitude of the threat missiles. Shorter powered flights of solid-fueled threat missiles require many more satellites for coverage. Shorter range missiles with their shorter burn times and lower burnout altitudes cannot be engaged by space-based boost-phase intercepts.
- The total life-cycle cost of placing and sustaining the constellation in orbit is at least an order of magnitude greater than that of any other alternative and impractical for that reason alone.

Overall Evaluation

Space-basing for boost-phase intercept would, in theory, solve the problems of proximity that make surface- and air-based boost-phase interceptors generally impractical. In principle, a constellation of satellites equipped with boost-phase interceptors could be configured so as always to be geographically in range for an intercept. The number of satellites required would depend in part on what threats are to be defended against. Shorter powered flight times for the threat missiles would require more satellites for coverage.

A space-based system would have to overcome objections (and, arguably, legal obstacles) to “weapons in space.” More important, a space-based system would be vulnerable to the sort of primitive ASAT device that a country capable of deploying an ICBM would probably be able to develop.

The most powerful objection to a space-based system, however, is the total acquisition cost (both initial and replacement satellite costs plus launch costs) for the large number of satellites needed for continuous coverage of potential threat launch locations because of the relative motion of satellites in orbit to Earth below (see Appendix J in the classified annex). Some 700 satellites would be required for defense against liquid-fueled ICBMs and some IRBMs, with some residual capability against solid-fueled ICBMs. For confident defense against solid-fuel ICBMs, as many as 1,600 to 2,000 satellites would be needed. The total life-cycle cost of developing, building, launching into orbit, and maintaining in orbit, even an austere and limited-capability network of 650 satellites, for example, would be approximately $300 billion (in FY 2010 dollars). The cost for greater capability would be correspondingly greater. From an annual acquisition cost perspective, these relatively high costs over the time frame estimated to provide operational space-basing for boost-phase interceptors would probably prove unaffordable.

Airborne-based interceptors (ABIs) have been proposed for boost-phase defense and possibly for terminal defense. All near-term systems on which the committee was briefed have very limited boost-phase capability (intercept ranges on the order of 50 km). The limited ranges of which a system would be capable do not allow boost-phase intercepts from outside the territory of even a small country such as North Korea. Such a system would be viable only if the aircraft could fly CAP for extended periods of time over enemy territory after air supremacy had been achieved.

3

Alternatives to U.S. Boost-Phase Defense

Table 3-1 displays U.S. boost-phase and non-boost defense alternatives—essentially, present and proposed ballistic missile defense (BMD) systems—that are examined in this report in the context of their potential mission applicability. The non-boost alternatives include the present and proposed systems beyond the boost phase of hostile missile flight—that is, in the ascent or "early intercept" phase, midcourse phase, and terminal phase. This chapter provides additional information on alternative systems to U.S. boost-phase missile defense as requested in the congressional tasking. Specifically, an overview and analysis of the Ground-Based Midcourse Defense (GMD) system; the Aegis ballistic missile defense system, with all variants of the standard missile-3 (SM-3) interceptor; the Terminal High-Altitude Area Defense (THAAD) system; the Patriot (PAC-3) system; and the Medium Extended Air Defense System (MEADS) is provided vis-à-vis their potential mission applicability.

TABLE 3-1 BMD Systems Examined in This Report in Terms of Their Potential Mission Applicability

Protected Area	Terminal	Midcourse	Ascent	Boost	Supporting Sensors
Homeland	**THAAD** **ALHK**	**GBI** **MKV** **SBI** **KEI**	**SM-3 Block IIB** **KEI** **SBI** **ALHK**	**SBI** **ABL** **KEI** **ALHK**	**DSP/SBIRS** **UEWR** **AN/TPY-2** **AN/SPY-1** **SBX** **STSS** **PTSS** **ABIR**
Allies	**SM-2 Block IV** **PAC-3** **THAAD** **MEADS**	**SM-3 Block I** **Two-stage GBI** **SM-3 Block II** **THAAD**	**SM-3 Block IIA** **SM-3 Block IIB** **KEI** **ALHK**	**ABL** **ALHK**	**DSP/SBIRS** **AN/TPY-2** **AN/SPY-1** **STSS** **PTSS** **ABIR** **Space-ISR** **A/B ISR**
Forces	**SM-2 Block IV** **PAC-3** **THAAD** **MEADS**	**SM-3 Block I** **SM-3 Block II** **THAAD**	**SM-3 Block IIA** **ALHK**	**ABL** **ALHK**	**DSP/SBIRS** **AN/TPY-2** **AN/SPY-1** **STSS** **PTSS** **ABIR** **RQ-4** **MQ-9**

NOTE: blue, operational; green, in development; purple, being considered; red, inactive, terminated, or redirected.

PRESENT AND PROPOSED SYSTEMS

Ground-Based Midcourse Defense System

The 2010 *Ballistic Missile Defense Review Report* states that "the United States is currently protected against limited ICBM attacks. This is a result of investments made over the past decade in a system based on GMD. Because of continuing improvements in the GMD System and the number of ground-based interceptors now deployed compared to potential North Korean and Iranian long-range ballistic missile capabilities, the United States possesses a capability to counter the projected threat from North Korea and Iran for the foreseeable future."[1]

The GMD program provides a ground-based midcourse interceptor for protection of the United States against ICBM threats. The National Missile Defense (NMD) program was established on April 1, 1997, and Boeing was chosen as the lead system integrator (LSI). Supplementing the Boeing effort on the booster, subcontractors include Raytheon for the exoatmospheric kill vehicle (EKV) and the sea-based X-band radar (SBX); TRW and Northrup Grumman for command and control, battle management, and communications (C2BMC); and the U.S. Army Corps of Engineers for construction. Currently, the program is in Phase B (product development), operating with an initial deployed capability. Key components of the GMD system include the ground-based interceptors (GBIs), located at Fort Greely, Alaska (FGA), and Vandenberg Air Force Base, California (VAFB); the Missile Defense Integrated Operations Center (MDIOC), located at Schriever Air Force Base, Colorado (SAFB); and the GMD Communication Network.

The GMD system interfaces with the BMD C2BMC system that provides target typing and tracks to the GMD fire control system. Once launched, the GBI communicates with BMD through the GMD fire control system using its in-flight communication system (IFCS) twice during the trajectory fly-out. The GBI interceptors exist in two variants, Capability Enhancement I (CE I) and Capability Enhancement II (CE II); the slight differences in software and hardware result in differences in communication range and discrimination strategies.

At FGA, the GMD system is operated by the 49th Missile Defense Battalion. Currently, Missile Field 1 with 6 silos and Missile Field 3 with 20 silos are operational. Missile Field 2 with 14 silos is under construction. Plans call for Missile Field 1 to be decommissioned following completion of Missile Field 2. At this time, 16 CE I interceptors and 5 CE II interceptors are located at FGA, with most of the interceptors operational at any given time. Additional components at FGA include a GMD fire control and system trainer, two command launch equipment sets, and two in-flight communication systems (IFCSs).

At VAFB, four CE I interceptors are housed among three operational launch facilities, one test launch facility, and one dual-purpose launch facility. VAFB also includes two relocatable IFCS data terminals.

The MDIOC, located at SAFB, contains two GMD fire control and system trainers, which nominally provide for the operational-level command of the GMD system, although the GMD system can be operated from the MDIOC, if necessary. The GMD system components at SAFB are operated by the Missile Defense Element of the 100th Missile Defense Brigade.

The final component of the GMD system is the GMD Communication Network, which is a system consisting of secure fiber- and satellite-communication links. Developed under MDA, the GMD Communication Network will be transferred to the Defense Information System Agency (DISA) in FY 2011 for maintenance and continued development.

In a typical engagement, a threat launch is detected by satellites and the BMD system is alerted. Cues are then issued to radars that detect and establish tracks, and if other criteria are met, interceptor release authority is granted. Engagements are controlled through the interceptor

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[1] Department of Defense. 2010. *Ballistic Missile Defense Review Report*, Washington, D.C., February.

midcourse phase. Following weapons release and the three-stage rocket firings of the GBI, the IFCS is used to relay in-flight target updates (IFTUs) to the EKV and to receive in-flight interceptor status reports during the first communication event (see classified Appendix J for greater detail).

Kinematically, the GBIs have sufficient performance to defend all of the continental United States (CONUS), although the existing system is most effective for the defense of the West Coast from attacks originating in east Asia. The defense of the U.S. East Coast against attack from southwest Asia suffers from the long duration of autonomous operations following its last IFCS event and the lack of early radar track information.

Table 3-2 lists BMD program investment costs, followed by the ground-based interceptor (GBI) average unit procurement recurring cost breakdown of the missile interceptors.

TABLE 3-2 GMD System Investment Costs Through FY 2009 and Interceptor Average Unit Production Costs (FY 2010 dollars)[a]

	Program Time Frame	Total Investment (billion $)	Average Annual Investment (million $)	AUPC (million $)
Boost-phase interceptor	1993-1999	1.4	227	
NMD DEM/VAL	1997-2001	8.7	1,444	
BMD system interceptor	2003-2009	1.9	265	
GMD block development	2002-2009	21.7	2,716	
Total investment		33.7		
GBI cost elements				
EKV				29.8
Boost stack				19.8
Boost avionics modules				6.5
Integration, assembly, and test				14.1
Total cost				70.2
Total cost of next five GBIs				86.5

[a] The current GMD system and previous predecessor system total program acquisition (RDT&E and Procurement) investment sunk costs expended through FY 2009 are based on the sum of the fiscal year actuals reported from the FY 2012 MDA Future Years Defense Plan (FYDP) President's budget (PB) justification sheets submitted in February 2011 and previous MDA (formerly BMDO) annual PB justification sheets. The committee requested all life-cycle cost elements in constant FY 2010 dollars. MDA provided the committee with both the average unit production costs (AUPCs) for the previous cost for five GBIs and an upper bound estimate for the next five interceptors. Since the GBI costs were unlabeled, the committee assumed they were in constant FY 2010 dollars.

SOURCE: Missile Defense Agency. 2011. *Department of Defense Fiscal Year (FY) 2012 Budget Estimates,* Justification Book Volume 2, Research, Development, Test, and Evaluation, Defense-Wide Procurement, O&M, and MILCON, Washington, D.C., February.

Aegis System and Standard Missile 3 Variants

The Aegis system provides the U.S. Navy with a multimission capability for BMD, antiaircraft warfare (AAW), antisubmarine warfare (ASW), and antisurface warfare (ASuW). With respect to BMD, the Aegis system has an existing capability deployed for sea-based midcourse defense and terminal defense and is in Phase A (concept development) and Phase B (product development) with a family of system improvements at different stages of development. The basic Aegis system consists of the AN/SPY-1 radar, Aegis BMD signal processor, Mark 41 vertical launch system (VLS), and SM-2 and SM-3 standard missiles. The SM-2 missile is designed for endoatmospheric terminal defense against maneuvering targets, and the SM-3 is designed for exoatmospheric intercepts against ballistic targets.

The Aegis system is capable of operating autonomously using organic sensors against short-range ballistic missile (SRBM) and medium-range ballistic missile (MRBM) threats. Recently, the capability has been added to operate in a launch-on-remote (LOR) mode, whereby the missile launching ship does not maintain its own track of the target at launch but rather uses information from other Aegis or BMD sensors (e.g., a land-based AN/TPY-2 radar). In the LOR concept, the engagement is controlled and in-flight target updates are provided from the launching ship. The Aegis program is also working to develop an engage-on-remote (EOR) capability by 2015, wherein the interceptor can be launched using any available target track and engagement is controlled from in-flight target updates that can be provided to the interceptor missile from any Aegis AN/SPY-1 or AN/TYP-2 radar. By 2015 this projected capability will significantly improve the utlility of the SM-3 Block II in both early and late midcourse engagements.

Since its first successful BMD intercept in January 2002, the Aegis system has undergone an extensive series of flight tests, including tests with no notice to the firing ship (Flight Test Mission (FTM) 04-1, February 2005), against a target with a separating warhead (FTM 04-2, November 2005), in conjunction with coalition partners (FTM 10, June 2006), against simultaneous BMD and AAW threats (FTM 11, April 2007), against dual SRBM targets (FTM 13, November 2007), and using LOR operations (satellite intercept, February 2008). The first fleet firing of the SM-3 occurred during PACBLITZ 08 in November 2008.

The Aegis BMD provides a proven capability for midcourse defense against certain classes of SRBMs and MRBMs. The system has the advantage of being housed on ships, so redeployment of BMD assets is possible, providing flexibility in the defense system. One challenge associated with the integration of the BMD capability on the Aegis multimission platform is that the competing missions may sometimes require deployment in nonideal locations from the BMD perspective.

Kinematically, the Aegis interceptors have about 50 percent of the burnout velocity provided by the GBI, which results in a more limited defended area, and its smaller kinetic kill vehicle (KKV) divert capability requires more accurate target tracking prior to committing the SM-3 interceptor missile.

The standard missile SM-3 Block IA interceptor missile together with Aegis weapon system (AWS) 3.6.1 is currently deployed for defense against short- and medium-range ballistic missiles and has a limited capability against intermediate-range ballistic missiles (IRBMs). Initially deployed in 2006, 112 missiles will be acquired by the end of FY 2012.

The SM-3 Block IA missile is launched from the Mk-41 VLS and consists of a 21-in. diameter Mk 72 booster, a 13.6-in. diameter Mk-104 dual-thrust rocket motor (DTRM), a 13.6-in. diameter third-stage rocket motor (TSRM), and a kill vehicle (KV) that uses a solid DACS and a one-color sensor. The KV maintains continuous communications with the launch platform throughout its full trajectory. AWS 3.6.1 retains the multimission capability for AAW, ASW, and ASuW. Following launch of the SM-3 Block 1A, the missile is command guided through its first three stages.

The sea-based terminal Aegis capability is provided using the SM-2 Block IV missile. Originally deployed in 2008, this system has performance against SRBMs and MRBMs. The SM-2 Block IV interceptor consists of the Mk-72 booster, Mk-104 DTRM, a blast fragmenting warhead, and a semiactive guidance system. The SM-2 Block IV missile provides an endoatmospheric intercept capability against maneuvering targets. A long-term replacement for the sea-based terminal interceptor is currently under development in a Phase A (concept exploration) program. This interceptor may also have some limited boost-phase defense capability against boosting targets in the atmosphere, provided the ship is close to the target missile launch location.

Table 3-3 lists the total investment cost of approximately $17 billion and the average annual investment costs for the previous and current BMD Aegis programs from FY 1964 through FY 2009. The table includes all the predecessor program investments beginning with the initial Navy-funded investments in the Aegis program, which consisted of both the development of the SM-2 (RIM-66C) missile and the AN/SPY-1A radar beginning in FY 1964 and continuing forward with SM-2 Block I through IV program development efforts through FY 2002. In parallel, the Ballistic Missile Defense Organization (the original name) and now the MDA continued parallel program investments to develop, first, sea-based and Navy theater area ballistic missiles beginning in FY 1993, followed by the procurement of SM-2 Blocks IV and V interceptors as well as VLS canisters in the FY 1999 through FY 2001 time frame.

TABLE 3-3 Aegis System Investment Costs Through FY-2009 (FY 2010 dollars)

Item	Program Time Frame	Total Investment (billion $)	Average Annual Investment (million $)
Navy Aegis weapon system (RIM-66C SM-2 and AN/SPY-1A)	1964-1985	2.5	115
Navy Aegis SM-2 Blocks I to IV	1987- 2002	1.2	140
Sea-based/Navy theater area TBMD DEM/VAL and EMD	1993-2002	6.2	686
SM-2 Blocks IVA and V and VLS canisters procurement	1999-2001	0.3	93
BMD Aegis block development	2002-2009	6.9	865
BMD Aegis procurement	2009	0.1	103
Total Navy and MDA investment		16.9	

NOTE: EMD, engineering and manufacturing development.
SOURCE: Missile Defense Agency. 2011. *Department of Defense Fiscal Year (FY) 2012 Budget Estimates*, Justification Book Volume 2, Research, Development, Test, and Evaluation, Defense-Wide Procurement, O&M, and MILCON, Washington, D.C., February.

Phased Adaptive Approach

This new program was announced in September 2009 as a shield against Iranian ballistic missile threats. Referred to as the Phase Adaptive Approach (PAA), the program has two primary objectives that are often merged in public releases, causing confusion: (1) Phases 1, 2, and 3 of PAA are evolutions to provide defense of Europe against MRBM and IRBM threats and (2) Phase 4 of PAA, which is not yet well defined but is specifically aimed at improving protection of the eastern United States against the potential of eventual introduction of Iranian intercontinental ballistic missiles (ICBMs).

PAA reflects a change in the intelligence community's estimates that indicated an acceleration in the development of Iranian IRBMs and a slowdown in the development of ICBMs. The four-phased approach was planned to begin in 2011 and is projected for completion in 2020.

As discussed later, the committee believes there should be a clear distinction between Phases 1, 2, and 3 and its objectives, on the one hand, and on the other, Phase 4, which adds little or nothing to the defense of Europe and is aimed primarily at adding an early shot opportunity to enhance the defense of the United States. Because PAA is still evolving, the details on siting, host nation support, force structure, cost estimates, command and control, concepts of operations, security, logistics support, were not available to the committee.

Phase 1 was planned to be completed in 2011 and consists of the deployment of Aegis naval assets equipped when necessary with the SM-3 Block 1A for the protection of portions of southern Europe against IRBMs.

Phase 2, projected to be completed by 2015, entails the introduction at sea and on land of the SM-3 Block IB interceptor, which is under development. The land-based sites will significantly improve the defense of NATO nations against IRBMs. Under Phase 2, Aegis BMD 4.0.1 will be certified for use in 2012. Included in this upgrade is the deployment of the SM-3 Block IB interceptor, which is currently being developed in a Phase B (product development) program. The principal changes include upgrading the KV to contain a two-color sensor and a throttleable DACS and modifications of the Aegis system to enable an increase in the number of simultaneous engagements. A total of 324 missiles are to be acquired between FY 2011 and FY 2018.

Phase 3, planned to be completed in 2018, adds the SM-3 Block IIA interceptor and will provide full NATO protection against Iranian SRBMs, MRBMs, and IRBMs (except for eastern Turkey, for which separate defenses would be required because of the potentially very short attack trajectories). Under Phase 3, the Aegis BMD 5.1 system will be certified for use by 2015. This missile is currently in Phase A of cooperative development with Japan. Studies are under way looking at conceptual canisters and boosters that can be operated from either ship or shore. The Aegis ashore program is currently in Phase B (product development) and consists of moving SM-3 Block IIA interceptors and their launching system to ground-based locations to provide greater midcourse intercept capability over large landmasses. Initial deployment is planned for FY 2015 at a single site.

Phase 4 is projected to be completed by 2020 and assumes the deployment of an even more advanced SM-3 with better performance. It is projected to have an ICBM capability and a kill capability for missiles in the ascent phase, and it will further augment the GMD system for the defense of the United States.

Terminal High-Altitude Area Defense System

The THAAD system is being developed to enable both endoatmospheric and exoatmospheric intercepts, primarily of SRBMs and MRBMs. In combination with Aegis, it may also provide defense of high-value, small-area targets against longer-range missiles. The system, which is designed to be deployable on C-17 aircraft, consists of six mobile launchers with eight interceptor missiles per launcher, AN/TPY-2 X-band radar, and the THAAD fire control and communications (TFCC) system housed within two tactical station groups. Plans called for a fielded capability by 2011 with 2 batteries and 50 interceptor missiles available. To date, 10 flight tests have been conducted, with six of six successful intercepts having been executed.

The AN/TPY-2 X-band radar consists of the antenna equipment unit (AEU), the electronic equipment unit (EEU), the cooling equipment unit (CEU), and the prime power unit (PPU); it serves both search and fire control functions.

The TFCC consists of the tactical operations station (TOS), the launch control station (LCS), the antenna support vehicle (ASV), and the cable support vehicle (CSV).

The interceptor missiles consist of a single-stage solid rocket with thrust-vector control and a KV that can maneuver both above the atmosphere as well as in the upper endosphere. The KV has a liquid bipropellant DACS, communications transponder and antenna, uncooled sapphire window, and a single-color midwave IR gimbaled seeker.

An engagement begins with the AN/TPY-2 radar, through either cueing or through its surveillance, detecting, and initiating target tracks. The radar collects medium-band and wide-band target features for discrimination before the interceptor is released by the TFCC. A TOM is developed from the radar and the designated target is identified. As many as seven IFTUs are provided during the interceptor fly-out. Final target discrimination is achieved through TOM alignment and onboard IR discrimination.

The THAAD system investment began with BMDO funding a DEM/VAL program beginning in FY 1992 and continuing through an engineering, manufacturing, and development (EMD) program through FY 2003 for the missile system, which includes the tactical support group (TSG), launcher, and ground-based radar. Table 3-4 lists the total annual investment of over $16 billion in the THAAD system from FY 1992 through FY 2009. This investment includes the average annual investment over the first two phases of the development program through preplanned product improvement of $872 million over this initial 12-year time frame, followed by the MDA THAAD block development program continuing through the 6 years from FY 2004 through FY 2009 at an approximately 29 percent higher annual investment of over $1.1 billion per year. As of the MDA FY 2011 FYDP budget, the THAAD program is completing development and being deployed. The program began expending procurement funds in FY 2009 for low-rate initial production (LRIP). Even though the first 50 THAAD interceptors were produced using RDT&E funds, the average missile unit costs are based on reported annual procurement budgets and lot quantity buys beginning in FY 2010 and continuing at the rate of 72 per year from FY 2013 through FY 2015.

TABLE 3-4 THAAD System Investment Costs Through FY 2009 (FY 2010 dollars)

Item	Program Time Frame	Total Investment (billion $)	Average Annual Investment (million $)
THAAD DEM/VAL, EMD and P3I (including ground-based radar)	1992-2003	9.6	872
THAAD block development	2004-2009	6.7	1,123
THAAD procurement	2009	0.1	106
Total Investment		16.4	

SOURCE: Missile Defense Agency. 2011. *Department of Defense Fiscal Year (FY) 2012 Budget Estimates*, Justification Book Volume 2, Research, Development, Test, and Evaluation, Defense-Wide Procurement, O&M, and MILCON, Washington, D.C., February.

Patriot System

The PAC-3 system allows the U.S. Army to provide air defense protection against TBM threats, air-breathing threats (ABTs), and cruise missile (CM) threats to critical assets and maneuver forces belonging to a corps and to echelons above corps.

The PAC-3 achieved initial operating capability (IOC) in June 2004 with a full battalion consisting of fire units and missiles. A firing battery consists of a multifunctional phased-array radar set (RS), an electronic power plant (EPP), an engagement control station (ECS), and two dual-capable PAC-3 launcher stations. A radar provides surveillance and missile guidance from launch through midcourse maneuver, terminal engagement, and intercept.

Following target acquisition by the radar, the target trajectory and intercept point are supplied by the fire control system. The missile is launched with an inertial fly-out toward the predicted intercept, with command guidance during midcourse. Following onboard acquisition of the target, terminal homing is provided using rapid response attitude control thrusters with the active missile seeker providing the necessary guidance accuracy. In the endgame following final homing maneuvers, the lethality enhancement system is fired.

The PAC-3 has conducted 31 successful flight tests since 1997 for an average of over two flight tests per year. There were also four PAC-3 missiles launched at TBMs in 2003 during Operation Iraqi Freedom. An improved version of the PAC-3 missile, called missile segment enhancement (MSE), is currently in development. Higher altitudes and longer intercept ranges will be achieved using a new dual-pulse rocket motor. The MSE will also include a redesigned lethality enhancement system.

Table 3-5 summarizes the total DOD and U.S. Army investment of close to $16 billion from FY 1983 through FY 2009 beginning with the PAC-3 development program and continuing forward for 21 years to FY 2003 at an average investment of $183 million per year. Since FY 2004, the investment in PAC-3 was and still is primarily the responsibility of the U.S. Army (as highlighted in green), including the commitment of procurement funding for producing a total of 975 missiles through FY 2009. The Army's LRIP of PAC-3 missiles began in the fourth quarter of FY 1999 and the first unit was delivered in September 2001.[2] The system IOT&E was completed by September 2002 and IOC was declared in June 2004. Operations central (OC) was achieved when the first PAC-3 operational battalion was fully equipped with five fire units (FUs) and 32 PAC-3 missiles per FU. By the end of FY 2003, 268 missiles had been produced, and the U.S. Army procured another 707 missiles through FY 2009.

TABLE 3-5 PAC-3 System Investment Costs through FY 2009 (FY 2010 dollars).

	Program Time Frame	Total Investment (billion $)	Average Annual Investment (million $)
PAC-3 RDT&E (defense-wide)	1983-2003	3.8	183
Army PAC-3 RDT&E	2004-2005	0.2	122
Army PAC-3 procurement (QTY = 975)	1997-2009	9.0	696
Army PAC-3 modifications	2000 (est.)-2009	2.8	282
Total DOD and Army investments		15.7	

SOURCE: Missile Defense Agency. 2011. *Department of Defense Fiscal Year (FY) 2012 Budget Estimates*, Justification Book Volume 2, Research, Development, Test, and Evaluation, Defense-Wide Procurement, O&M, and MILCON, Washington, D.C., February.

Medium Extended Air Defense System

MEADS is or was a trinational codevelopment program that aimed to meet the future air and terminal missile defense needs of the United States, Germany, and Italy. As such, it was envisioned as a replacement for the Patriot, Hawk, and Nike Hercules systems. The program was directed and administered by a trinational steering committee. The U.S. MEADS program office executed the day-to-day management on behalf of the U.S. steering committee member.

MEADS has tenuous support in the United States, and the limited data and justification provided to the committee were therefore not analyzed. Originally awarded in 2004, the program had an objective for U.S. IOC in 2017. The system was being designed to have capability against theater ballistic missiles (TBMs), manned aircraft, cruise missiles, unmanned aerial vehicles (UAVs), and tactical air-to-surface missiles.

Within MEADS, a typical fire control unit would consist of two BMC4I systems, a surveillance radar, two multifunction fire-control radars, six launchers with 48 interceptors, and three reloaders. The pulsed Doppler surveillance would operate at UHF and provide 360-degree coverage using a phased-array antenna. The multifunctional fire control radar would operate at X-band with a phased-array antenna and would also provide 360-degree coverage.

ANALYSIS

As previously noted, this study is focused on assessing U.S. boost-phase missile defense and non-boost defense alternatives to countering the threats identified in the congressional tasking (e.g., SRBM, MRBM, IRBM, and ICBM threats) in terms of their ability to carry out the established missile defense missions, all of which are congruent with those established in 2010 by the DOD in its ballistic missile defense report:[3] (1) protection of the U.S. homeland against nuclear attacks, other weapons of mass destruction (WMD), or conventional ballistic missile attacks; (2) protection of U.S. forces, including military bases, in theaters of operation against ballistic missile attacks; and (3) protection of U.S. allies, partners, and host nations against ballistic-missile-delivered WMD and conventional weapons.[4] A fourth mission was considered

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[2] The majority of the PAC-3 historical information was based on the Patriot PAC-3 Dec-09 Selected Acquisition Report (SAR) and the Army FY-11 RDT&E and Procurement Budget submitted in February 2010.

[3] See Department of Defense, 2010, *Ballistic Missile Defense Report*, Washington, D.C., February.

[4] For brevity, missions (2) and (3) are usually considered together because they so often defend against hostile missiles of similar character although being defended against for different purposes.

as a collateral benefit but not as a requirements-defining mission: protection of the U.S. homeland, allies, and partners against accidental or unauthorized launch.[5,6]

Over the course of this study, several tools were used to explore attributes of the existing system, to evaluate potential increments to the existing system, and to assess the performance of a modified system using new conceptual designs. The classified annex that accompanies this unclassified report provides a detailed analysis of the present and proposed systems for U.S. boost-phase missile defense and non-boost alternatives in the context of their potential mission applicability. The following section provides an unclassified analysis that is based on a notional set of threat missiles, interceptor designs and sensors where fly-out velocity has been varied parametrically to explore the basic physical limitations of missile defense system performance. Findings are then provided. In Chapter 4 , a summary table of the systems for U.S. boost-phase missile defense and of non-boost alternatives is provided, in addition to other unclassified information.

Homeland Defense: GMD and PAA Phase 4 and Early Intercept of Threats Against the Eastern United States

GMD System

The GMD system as currently configured has the kinematic capability of GBI to defend large geographic areas if early threat track data of sufficient quality can be provided for interceptor commit. The current GMD system configuration is northeast Asia-centric for defense of the western part of CONUS and Alaska. Moreover, it is limited to an inefficient firing doctrine. Currently, there are limitations in protecting the eastern United States from a threat from the Middle East, as detailed in classified Appendix J. The boundaries of the existing GBI kinematic performance envelope are established by the powered-flight exclusion zone (commonly referred to as the interceptor “dead zone”) around the interceptor launch location shown as the notch around the origin (see Figure J-1 in Appendix J of the classified annex). The maximum interceptor time of flight and burnout velocity establish the outer boundary. The size of the powered-flight exclusion zone is established by the GBI burnout velocity and total burn time of the booster including any coast periods between stages and EKV separation from the final stage plus the minimum time it takes to orient the EKV and engage the target. A minimum EKV operation time results in a second powered-flight exclusion boundary. The outer boundary is driven primarily by EKV coolant supply and the useful life of the thermal batteries used to power the guidance and control systems on the EKV. However, in a tactical engagement situation, many other factors may come into play that reduce the outer boundary of the kinematic envelope. Examples include interceptor launch delays caused by weapons release authorization; availability of data on launch quality from the forward sensor; communication link limits of the interceptor data terminals (IDTs) in providing IFTUs and TOM handovers to the EKV for acquisition and target discrimination; sun, moon, and Earth limb viewing avoidance during EKV target acquisition and homing; and maximum divert capability of the EKV to take out initial

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[5] Any BMD system would provide some inherent capabilities for defense against accidental or unauthorized launch of a Russian or Chinese missile or, for that matter, one owned by another power. However, defense against such attacks should not drive the design or evaluation of defense concepts, because the greater sophistication (or numbers) of such an attack would tend to establish unrealistic and perhaps infeasible or unaffordable requirements compared to those appropriate for a defense focused on the rogue state threat.

[6] Aside from political and stability effects, such defense is not practical, given the size, sophistication, and capabilities of Russian and Chinese forces and both countries’ potential to respond to U.S. defense efforts, including by increasing the size of the attack to the point at which U.S. defenses are simply overwhelmed by numbers. The fourth mission is discussed in greater detail in the classified annex (Appendix J).

interceptor targeting errors. The lower boundary is at an altitude to ensure that the EKV is above the sensible Earth atmosphere for reliable LWIR sensor performance.

The implications of these limiting boundary conditions are that a powered-flight exclusion zone eats up the battle space around the threat midcourse trajectory. Significantly shorter burn boosters and shorter launch decision delays would improve engagement performance. Long-time-of-flight complications can be removed by having multiple widely dispersed interceptor sites to reduce the need for extremely long-range, long-time-of-flight interceptor trajectories, which permits an SLS firing doctrine as opposed to a wasteful salvo firing doctrine, as discussed in classified Appendix J. It also permits more data collection on decision time and target for more accurate and reliable intercepts.[7] While it is kinematically possible to defend the eastern part of CONUS against threat ICBMs from the Middle East using GBI sites at FGA and VAFB, an additional GBI site located in northeastern CONUS would be much more effective and reliable and would allow considerably more battle space and firing doctrine options. The current GMD system architecture must be and can be fixed, as discussed in Chapter 5.

Early Intercept of Threats Against the Eastern United States: Phase 4 of PAA

Separate and distinct from Phases 1, 2, and 3, Phase 4 of PAA has as a long-term objective the provision of "early" intercepts of threats from the Middle East to the eastern United States, which is poorly protected by the current GMD system. This is a complex issue for three reasons: (1) the limitations of the existing GMD system and the modifications it requires; (2) the size of interceptors needed in Europe to provide an "early" shot without being overflown; and (3) the perceived threat of such interceptors to portions of the Russian Federation's strategic deterrent force and the effect on U.S.-Russian relations. It seems further complicated by NATO missile defense objectives and how Russian participation in European defense should and could be achieved.

The committee's assessment of the Phase 4 early intercept augmentation of homeland defense can be summarized as follows. The early intercept of potential threats to the United States would require an interceptor with a fly-out velocity greater than 5 km/sec at the European site to avoid being overflown by modestly lofted threats to the U.S. East Coast. For example, Figure 3-1 shows notional ICBM trajectories headed for the U.S. East Coast flying directly over a notional interceptor with a fly-out velocity greater than 4 km/sec based at the Poland site, but that is less than that which could threaten any portions of the Russian Federation's strategic deterrent force. A slightly lofted ICBM (solid red) can overfly the kinematic capability of such an interceptor.

The old controversial third site with a two-stage GBI was based on providing such capability. Even then, to provide an early shot ahead of the FGA-based interceptors protecting the western United States, the field of fire of Poland-based interceptors would be constrained to a tail chase engagement geometry to avoid dropping interceptor stages on populated areas of the Russian Federation, another likely bone of contention. Here, a notional interceptor based in Poland such as that described in Figure 3-1 would not threaten any portions of the Russian

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[7] In the 2011 *Defense Science Board Task Force Report on Science and Technology Issues of Early Intercept Ballistic Missile Defense Feasibility*, it was noted, among other things, that "If, as an alternative to simply firing salvos of defense missile at each incoming missile, time is available to fire one missile, observe what happens from that engagement, and then fire the remaining missile(s) only if the assessment is made that the first shot was not successful, then the potential exists to save significant defense resources." 2011 Defense Science Board. *Defense Science Board Task Force Report on Science and Technology Issues of Early Intercept Ballistic Missile Defense Feasibility*. Office of Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., September.

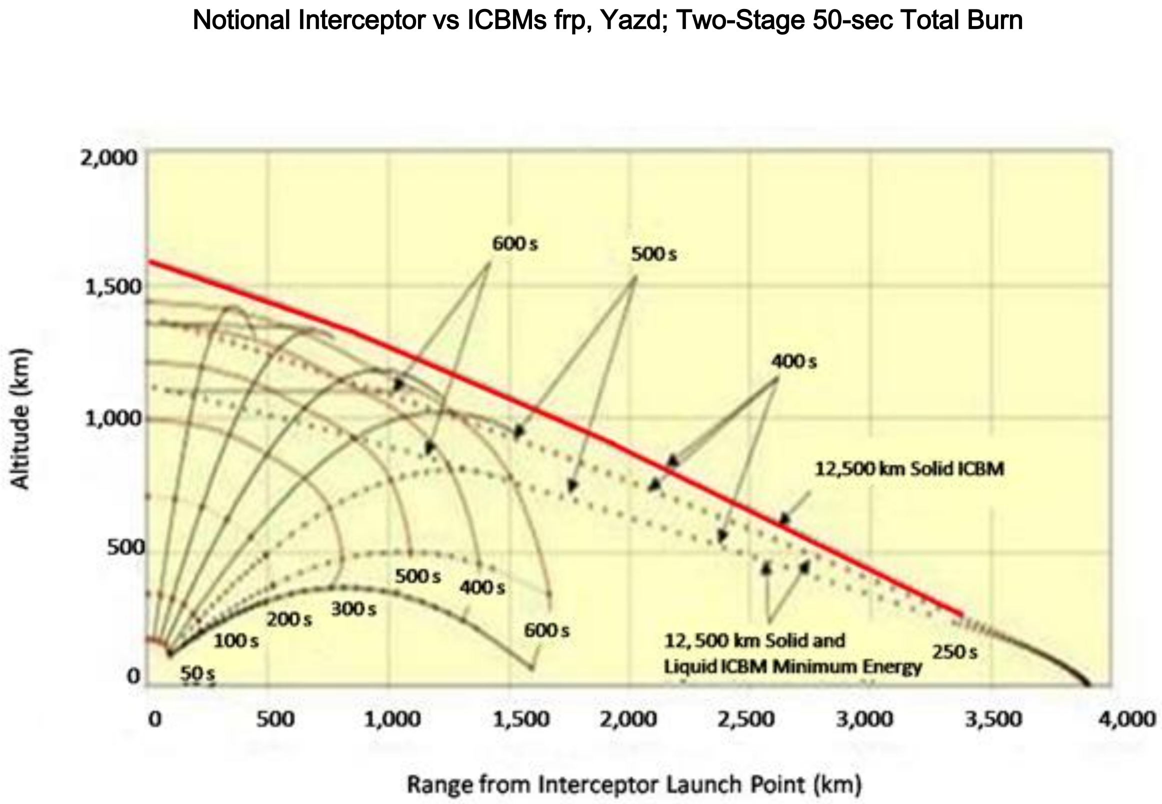

FIGURE 3-1 Notional ICBM trajectories from Iran to U.S. East Coast.

Federation's strategic deterrent force, would provide good coverage of Europe, and might be of value to homeland defense under circumstances discussed later in Chapter 5.

If no AN/TPY-2 radar site is available in Turkey, Armenia, Georgia, or another suitable location, the loss of early tracking and discrimination data would preclude the early intercept of threats from Iran to the United States and would erode coverage for European defense.[8] One solution would be to base a radar on the Black Sea coast of Romania. However, an AN/TPY-2 at that location would not have sufficient range to avoid being overflown by threats to western Europe, and coverage against MRBM threats would consequently be reduced. Therefore, a GBX version, described in Chapter 4, would be required at that location. Another potential alternative being considered by MDA would be a version of the airborne infrared (ABIR) unmanned system flying CAP, perhaps over the eastern Black Sea. Cost should be a strong consideration in the event an alternative to the forward-based radar is needed.

The committee's analysis suggested that any long-range missiles would likely be based deeper in the heartland of Iran, near Yazd, while shorter range missiles would be based near Tabriz. The basing of ICBMs or MRBMs in silos near Qom raises a question about the value of an Aegis ship in the Black Sea. The committee set aside the obvious operations issues of maintaining an Aegis ship in the southeastern Black Sea in examining engagement effectiveness (see classified Appendix J for greater detail).

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[8] The Obama administration signed an accord with Turkey in September 2011 for the U.S. military to operate a high-power X-band radar station in Malatya Province, which is approximately 400 miles west of Iran. This new radar capability combined with similar U.S. naval ship radars is expected to provide early warning of Iranian missile activity.

Defense of Deployed Forces and U.S. Allies, Partners, and Host Nations

Deployed Forces: Aegis, PAC-3, and THAAD Systems

Against short- and medium-range threats, Aegis, THAAD, and PAC-3 are well developed and suited to their individual missions (e.g., defending deployed forces), but there has been limited interface among them. More attention is needed to the exchange of data and hardware among these systems to take full advantage of the large investment already made in the form of both procurement and operating costs. The newly awarded integrated battle command system (IBCS) is intended to integrate data from these systems and provide the needed battle management capabilities.

Inputs to the BMD data network already include those from the Defense Support Program (DSP), the SBIRS, and the UHF early warning radars. Maximum use must be made of these data to relieve X-band radars of unnecessary volume or fan search functions, allowing them to concentrate their resources on tracking and discrimination at the longer ranges permitted when properly cued to the targets. This involves little or no new investment.

Despite the recent cancellation of U.S. participation, it should be noted that the MEADS UHF surveillance radar has 360-degree coverage against ballistic missile targets from every direction. It could be a valuable addition to the BMD data network in support of THAAD and PAC-3 by allowing those organic radars to concentrate on fire control rather than also spending resources on surveillance.

A THAAD Block II interceptor has been proposed that would be fast enough to take full advantage of TPY-2 radar coverage. Such an interceptor, if pursued, would expand considerably the defended footprint for THAAD, reducing the number of batteries required to defend large areas against medium-range missiles by as much as 30 percent. A faster THAAD Block II interceptor would take full advantage of the TPY-2 radar. Since THAAD can take advantage of atmospheric filtering, such a THAAD Block II interceptor could provide for extended terminal defense coverage of high-priority targets.

THAAD and Aegis would operate as a layered midcourse defense and THAAD and PAC-3 as a layered terminal defense.

U.S. Allies, Partners, and Host Nations: Phases 1, 2, and 3 of PAA

The early phases of the PAA have remained relatively stable during the course of the study; however, their capabilities have not, particularly as discussions with European allies and the Russian Federation continue. In PAA, the United States has developed a near-term approach for the protection of Europe from now through the relatively near future based on the proven technologies of today as the Iranian MRBM and IRBM threats appear to be developing faster than previously had been envisioned. The proven systems are the SM-3 interceptor, the AN/TPY-2 radar, and, potentially, the airborne IRST sensors. As the threat evolves, extending the mission requirement to defend more or even all of Europe against MRBM and IRBM threats will require three Aegis-class sites still using the SM-3 Block IIA. Coverage of Israel and other Middle East areas against the evolved threat will require two additional sites, still using the same interceptor. (Turkey, of course, will require its separate defense using THAAD or equivalent against shorter-range threats.) These requirements assume single-shot defense of most areas is acceptable. Universal SLS capability—which is desirable for more effective protection—would require additional sites or terminal defense.

As was touched on, PAA has two primary objectives that are often merged in public discussions. However, there should be a clear distinction between these two objectives because they may lead to different development paths. Specifically, it appears that the first objective (i.e., Phases 1, 2, and 3 of PAA) is to provide an evolutionary protective umbrella for European and Middle Eastern allies initially against SRBM and MRBM threats such as the Iranian liquid-fueled Shahab 3, with a nominal range of about approximately 1,300 km, or the newer 2-stage solid-propellant MRBM, estimated to have a range approximately 2,000 km.[9] Later on, the capability would be expanded to protect against longer range IRBM threats to Europe. Meeting this first objective would also contribute to the protection of U.S. forces that are within the defended area. These forces and bases (installations), along with other high-value assets, could be further protected by an underlay of THAAD batteries whose radars could also support the LOR capability currently being tested to extend the reach of Aegis interceptors that are planned as the backbone of PAA.

In Phase 1 of PAA, before any new capabilities are available, existing Aegis ships with SM-3 Block 1A interceptors in the eastern and western Mediterranean and the North Sea can provide limited interim protection. If a THAAD radar were placed forward—for example, in eastern Turkey or, as currently in Israel—that radar, cued by SBIRS, would provide LOR data to increase the coverage of the SM-3 interceptors currently constrained by the SPY-1 shipboard radar. In Phase 2 of the PAA, two Aegis ashore sites—one at Deveselu, Romania, and another in northern Poland—are currently planned. Here, AN/TPY-2 radars that are forward based would support LOR capability and possibly EOR capability for Aegis SM-3 Block IB interceptors with improved KVs. Phase 3 of PAA would introduce the higher velocity SM-3 Block IIA interceptor and two new optical tracking systems to support early intercept.

The first of these two new optical tracking systems for Phase 3 of PAA is the persistent (or precision) tracking surveillance system (PTSS), which is proposed as a constellation of 12 satellites for cold-body tracking. The other proposed optical tracking system is the ABIR system, which is a two- or three-UAV system that is currently being field tested for early stereo threat tracking. As noted in Chapter 4, PTSS seems both unnecessary and far more expensive than other more effective alternative sensors for early track data using X-band radars. As noted in Chapter 4, ABIR is also not well defined.[10] Here, the new SM-3 Block IIA interceptor jointly developed with Japan was planned to provide substantially more performance than the SM-3 Block IA or IB by using a 21-in. second-stage rocket motor; however, it has fallen far short of its originally planned performance.

To meet the first objective of PAA, Phase 3 should include a capability for defending against IRBMs that could put virtually all of Europe and most of the United Kingdom at risk. The committee is aware that Iran appears to be working on larger solid rocket motors. For example, one can construct a notional two- or three-stage solid-propellant IRBM missile based on the same solid-propellant technology Iran has already demonstrated that could have a range of approximately 5,600 km. Such a missile would be capable of reaching virtually all of the Eurasian landmass.

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[9] Department of Defense. 2010. *Ballistic Missile Defense Review Report*, February, pp. 5-6.

[10] The analysis of future ABIR systems in this report is necessarily sketchy because the ABIR program of record was not well defined at the beginning of this study. Initially, the ABIR program was conceived as a Reaper drone using the existing multispectral targeting system (MTS)-B sensor ball as the infrared sensor, possibly with the MTS-B sensor moved toward the nose of the aircraft to allow better elevation viewing. Later the MTS-C sensor ball was suggested to add LWIR capability. Sensors similar to the High-Altitude Observatory 2 (HALO-2) Heimdall sensor have also been suggested. The committee did not attempt to assess the capability of different ABIR configurations. However, it should be noted that LWIR capability is essential for cold-body tracking. In addition, tracking through the zenith is required for long-duration midcourse data collection (comparable to requirements for PTSS). Moreover, ABIR LWIR detection ranges should be at least 1,000 km to avoid being overflown by IRBMs. For room temperature targets, this requires sensors with an aperture on the order of 20 cm, assuming that an LWIR system noise equivalent flux density (NEFD) on the order of 1×10^{-16} W/cm^2 can be achieved. For colder targets, lower NEFD figures of merit are required, which, in turn, requires cold optics—a potential challenge for airborne platforms. Finally, this system requires that two platforms be airborne simultaneously to provide stereo tracking for range data.

European Defense Analysis

Figures 3-2 to 3-9 illustrate the notional capability expected in the European PAA, where fly-out velocity is varied parametrically. Figure 3-2 displays the earliest and latest engagement opportunities of a notional 4-km/sec fly-out velocity interceptor against minimum energy threats from central Iran flying directly over the planned Deveselu, Romania site. This is the most defense-favorable engagement geometry possible from that site. Figure 3-2 also illustrates that a notional 4-km/sec interceptor at the Deveselu site could provide good coverage and substantial battle space against IRBM minimum-energy trajectories, assuming there is a forward-based radar that provides LOR capability.

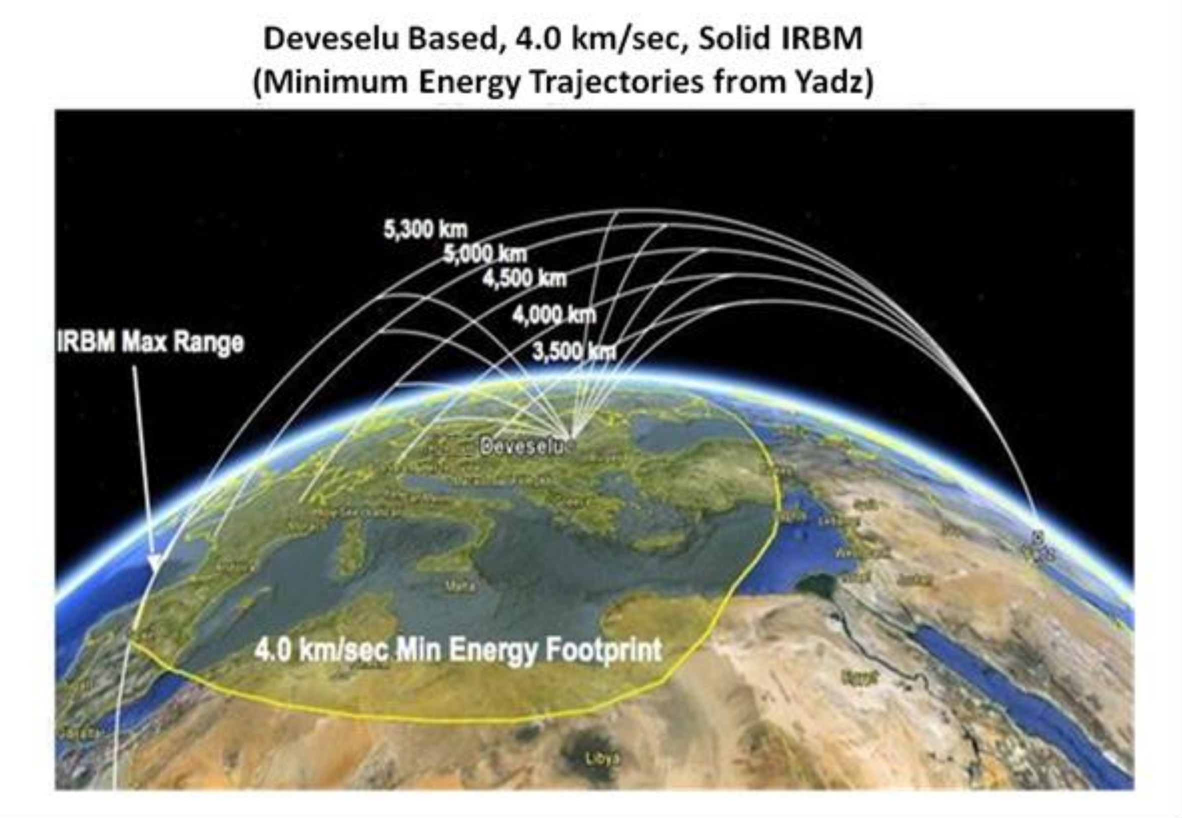

FIGURE 3-2 Notional engagement opportunities of a 4-km/sec fly-out velocity interceptor against minimum energy threats from central Iran flying directly over the planned Deveselu site.

Figure 3-3 shows the same interceptor's performance against trajectories moderately lofted. Such threats, which could reach 4,800 km or more to western Europe, could overfly the kinematic capability of the 4-km/sec interceptor at Deveselu. Thus, in order to protect southwestern Europe and the United Kingdom, one or two additional sites would probably be required if or when the longer range IRBMs emerge. A faster interceptor with a fly-out velocity greater than 5.5 km/sec would have a significantly longer reach and could not be overflown within Europe. This can best be seen by looking at the single-shot- and SLS-defended footprints in Figures 3-2 through 3-17 from notional engagement simulations performed during this study.[11]

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[11] These figures were generated from the committee's analysis using Google Earth. ©2011 Google, Map Data©2011 Tele Atlas.

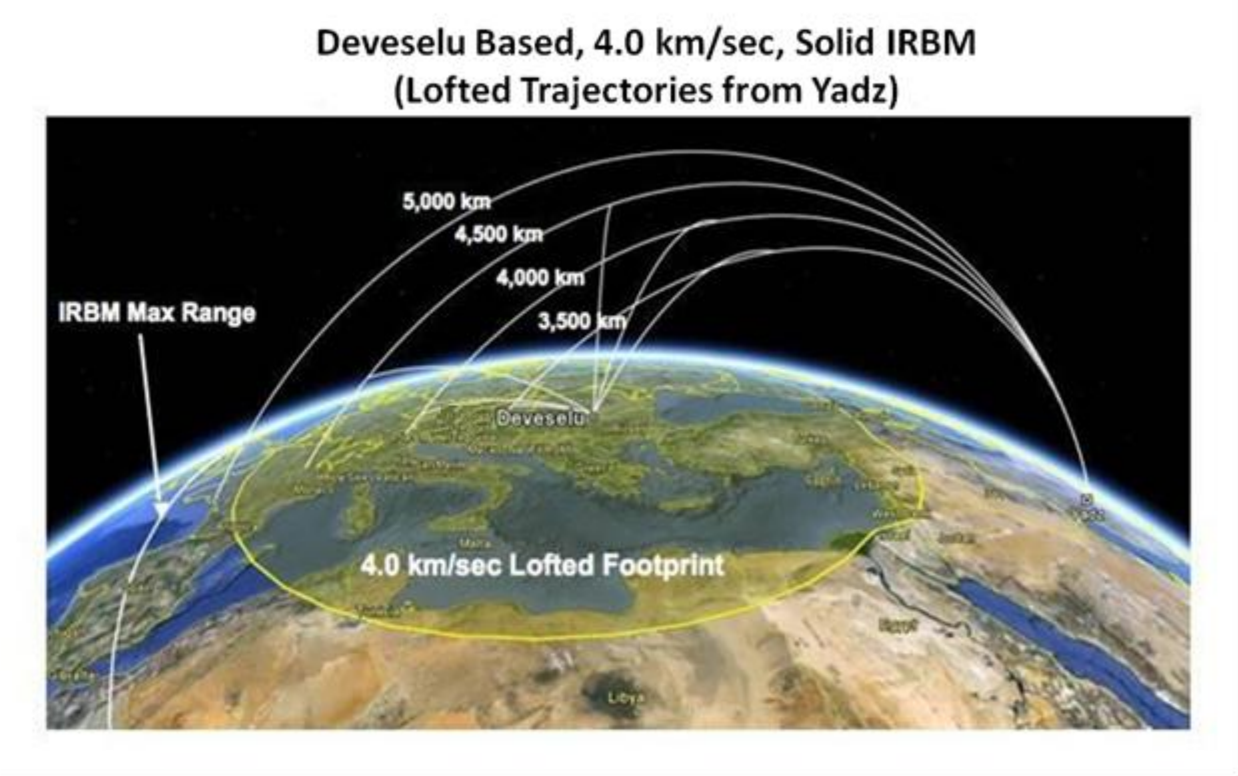

FIGURE 3-3 Notional engagement opportunities of a 4-km/sec fly-out velocity interceptor against moderately lofted threats from central Iran flying directly over the planned Deveselu site.

Single-shot coverage defines the maximum boundary of a defended area. SLS footprints delineate the area where SLS doctrine can be enforced. SLS battle space is a measure of robustness, important for allowing a delay in the decision to commit, for second-shot opportunities to take advantage of initial discrimination results, and for replacing intercept failures.

Figure 3-4 displays the resulting single-shot coverage for an interceptor with fly-out velocity varied parametrically between 3.0 and 4.5 km/sec in steps of 0.5 km/sec against minimum energy trajectories from central Iran, assuming EOR capability. Figure 3-5 and Figure 3-6 show the corresponding single-shot footprints for lofted trajectories and depressed trajectories, again assuming engage on remote. In all these examples, the western boundary, shown by the white arc, is determined by the maximum range assumed for the notional threat, not by notional interceptor performance.

Figure 3-7, Figure 3-8, and Figure 3-9 show the SLS footprints against minimum energy lofted and depressed trajectories from Iran for three different interceptor fly-out velocities varied parametrically based at Deveselu, Romania and in northern Poland, assuming EOR. In these cases no 3.0 km/sec interceptor capability was shown because its SLS footprints are either too small or nonexistent.

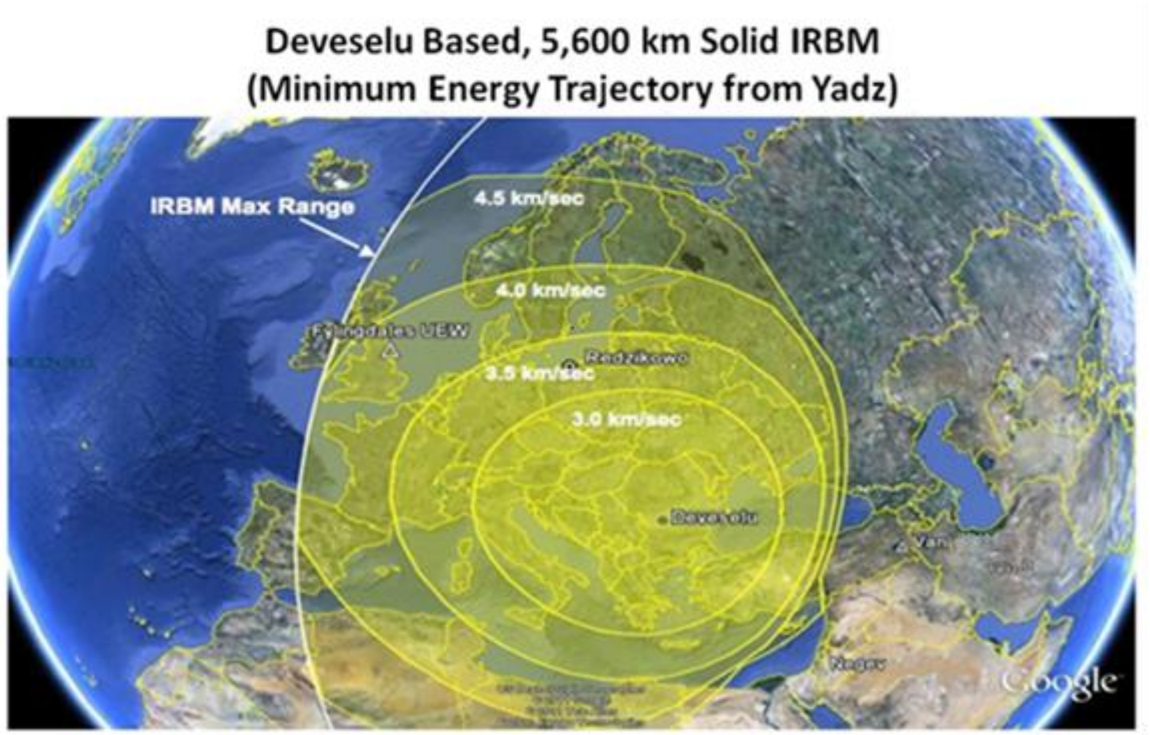

FIGURE 3-4 Notional single-shot coverage for interceptors with fly-out velocity varied parametrically between 3.0 and 4.5 km/sec against minimum energy notional 5,600-km solid IRBM trajectories from central Iran. EOR is assumed.

FIGURE 3-5 Notional single-shot coverage for interceptors with fly-out velocity varied parametrically between 3.0 km/sec to 4.5 km/sec against lofted trajectories from central Iran. EOR is assumed.

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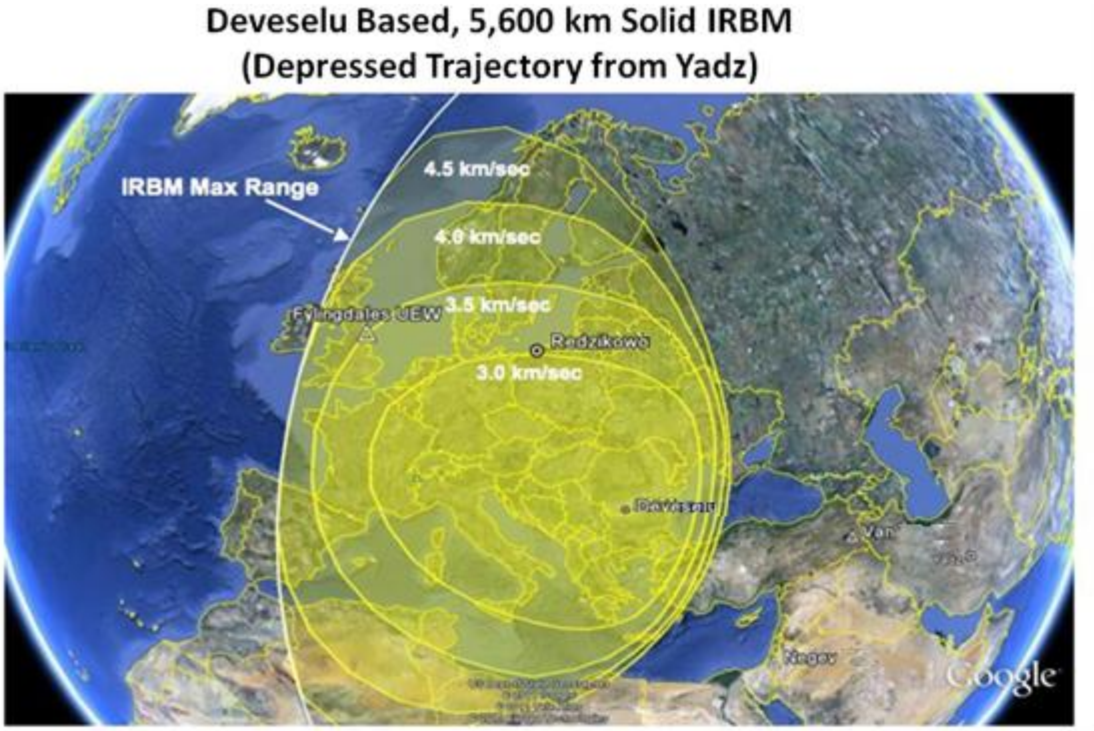

FIGURE 3-6 Notional single-shot coverage for interceptors with fly-out velocity varied parametrically between 3.0 and 4.5 km/sec against depressed trajectories from central Iran. EOR is assumed.

FIGURE 3-7 Notional SLS footprints against minimum energy trajectories from Iran for interceptors with fly-out velocity varied parametrically between 3.0 and 4.5 km/sec based at Deveselu, Romania, and Redzikowo, Poland. EOR is assumed.

FIGURE 3-8 Notional SLS footprints against lofted trajectories from Iran for interceptors with fly-out velocity varied parametrically between 3.0 and 4.5 km/sec based at Deveselu, Romania, and Predzikowo, Poland. EOR is assumed.

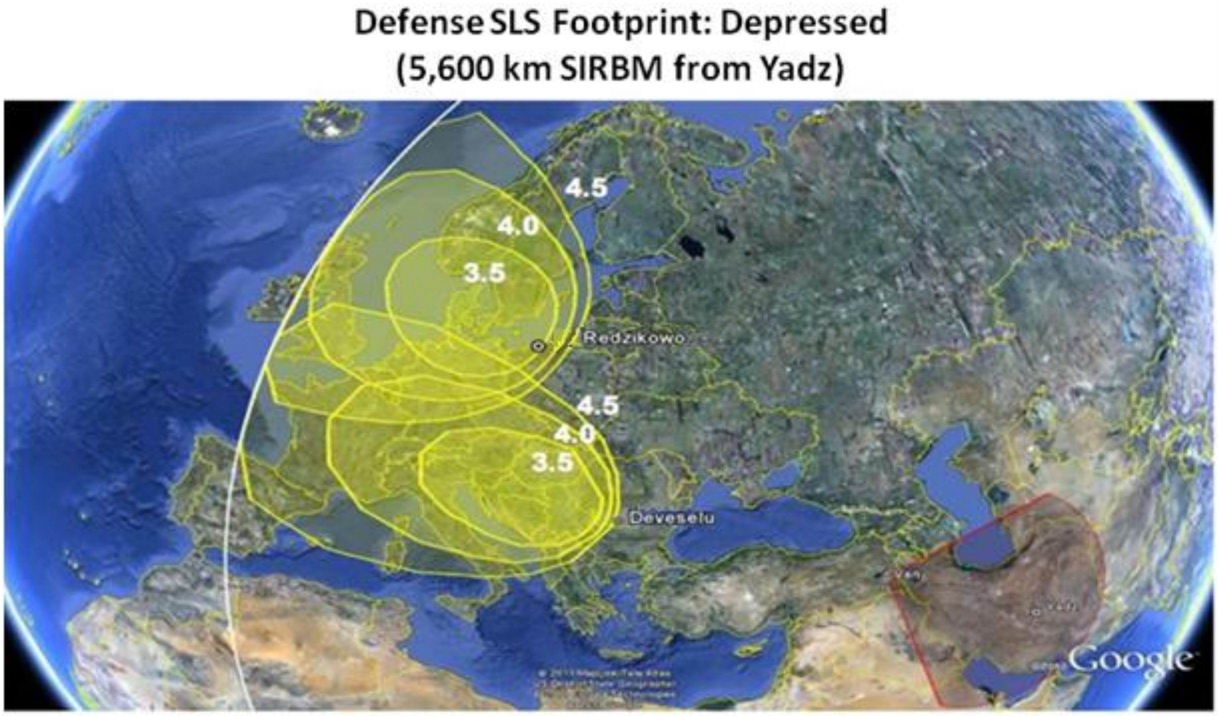

FIGURE 3-9 Notional SLS footprints against depressed trajectories from Iran for interceptors with fly-out velocity varied parametrically between 3.0 and 4.5 km/sec based at Deveselu, Romania, and Redzikowo, Poland. EOR is assumed.

The message of these figures is that an interceptor with fly-out velocity greater than 4.0 km/sec—and less than that which could threaten any portions of the Russian Federation's strategic deterrent force and is supported by forward-based X-band radar to provide LOR and

EOR capability—provides coverage of all of NATO Europe except eastern Turkey. This message is, however, subject to an important qualification—namely, because the interceptors and sensors could provide coverage of the continent does not automatically mean the defense will be successful. The engagements needed for regional defense will in virtually all cases be in midcourse, and the midcourse discrimination problem is not inherently any different for MRBM or IRBM engagements than for ICBMs. The PAA (and the parallel efforts in the Middle East and northeast Asia) depend for discrimination on the integration of information from radars (notably TPY-2). While this concept is right in principle, the challenge is to accomplish discrimination in practice, as demonstrated by rigorous and realistic testing.

Northeast Asia Defense Analysis

While most of the focus to this point has been on protecting Europe from evolving ballistic missile threats from Iran, the evolution of the Aegis shipboard interceptor and its interoperability with THAAD are also applicable to defense against the significant ballistic missile threat that North Korea poses to U.S. allies and U.S. military forces in northeast Asia. Japan is the first ally to participate seriously, by jointly developing with the United States an improved Aegis SM-3 Block IIA interceptor, which figures prominently in its self-defense and in Phase 3 of the PAA architecture.

Because of the short burn times and low altitude at burnout of missiles that could target Japan and Okinawa, boost-phase defense is not practical even with the favorable engagement geometry available from Aegis ships. Therefore midcourse and terminal defenses are the only practical options available.

Figure 3-10 illustrates the single-shot footprints one can expect for interceptors with fly-out velocity varied parametrically between 3.0 km/sec and 4.5 km/sec against North Korean MRBMs (range of approximately 1,300 km), assuming EOR capability and an assumed second forward-based AN/TPY-2 radar located near Hagi, Japan, to provide accurate track data. The interceptor fly-out velocity is varied parametrically between 3.0 km/sec and 4.5 km/sec. As can be seen, notional interceptors with speeds of about 3.0 km/sec with EOR are adequate for the single-shot defense of Japan. This is less true for LOR firing doctrines, as illustrated in Figure 3-11, and less so still if stand-alone operations are considered. The LOR footprint in Figure 3-11 does not vary with interceptor speed because it is constrained by the range of the radar, not the interceptor flight speed (at least for interceptors with speeds above 3.0 km/sec). Figures 3-12 and 3-13 illustrate the single-shot EOR footprints against lofted and depressed trajectory MRBM threats, respectively. From these figures, one can see that it takes only one site (located near the center of the Sea of Japan) to provide single-shot EOR coverage for all of Japan regardless of the trajectory on which a notional 1,300 km-range liquid-propellant MRBM flies, and two sites (i.e., ships on station in two areas in the Sea of Japan) if single-shot LOR firing doctrines obtain. If one considers a more widely dispersed set of potential launch locations in North Korea, two sites will be required for complete EOR coverage of Japan, at least for the slower interceptor speeds considered here, and at least two sites in the case of LOR operation.

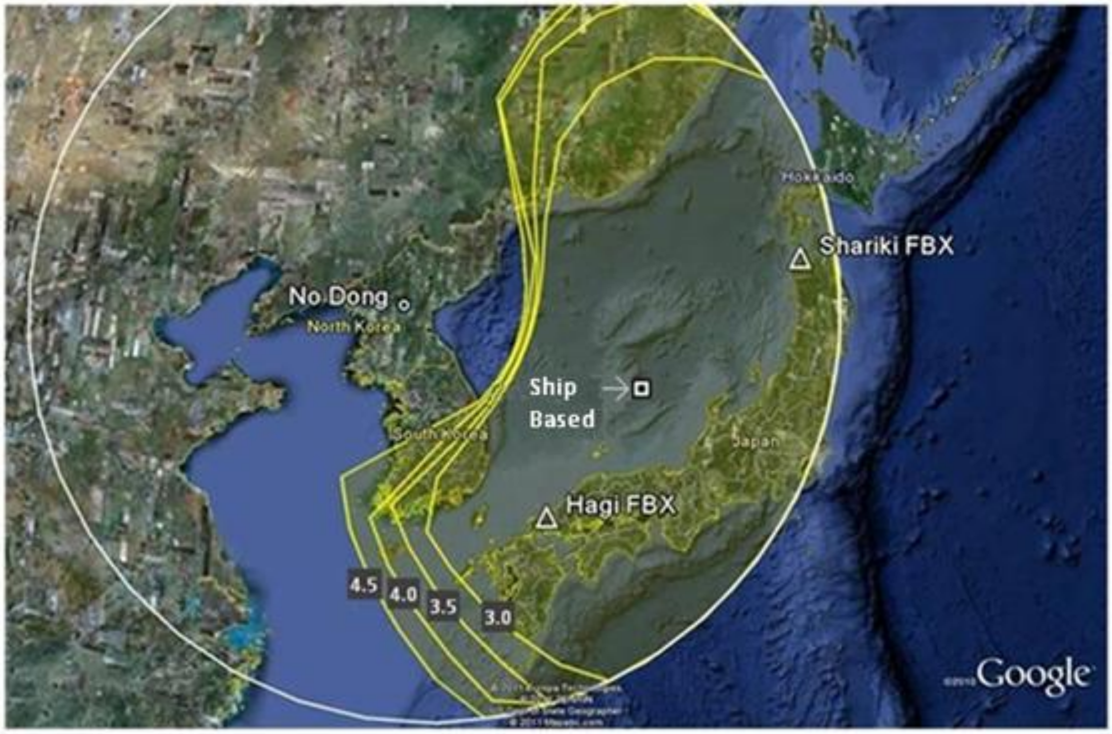

FIGURE 3-10 Notional ship-based single-shot EOR coverage of Japan: minimum energy MRBM trajectories. Note Hagi FBX location is notional and EOR is assumed.

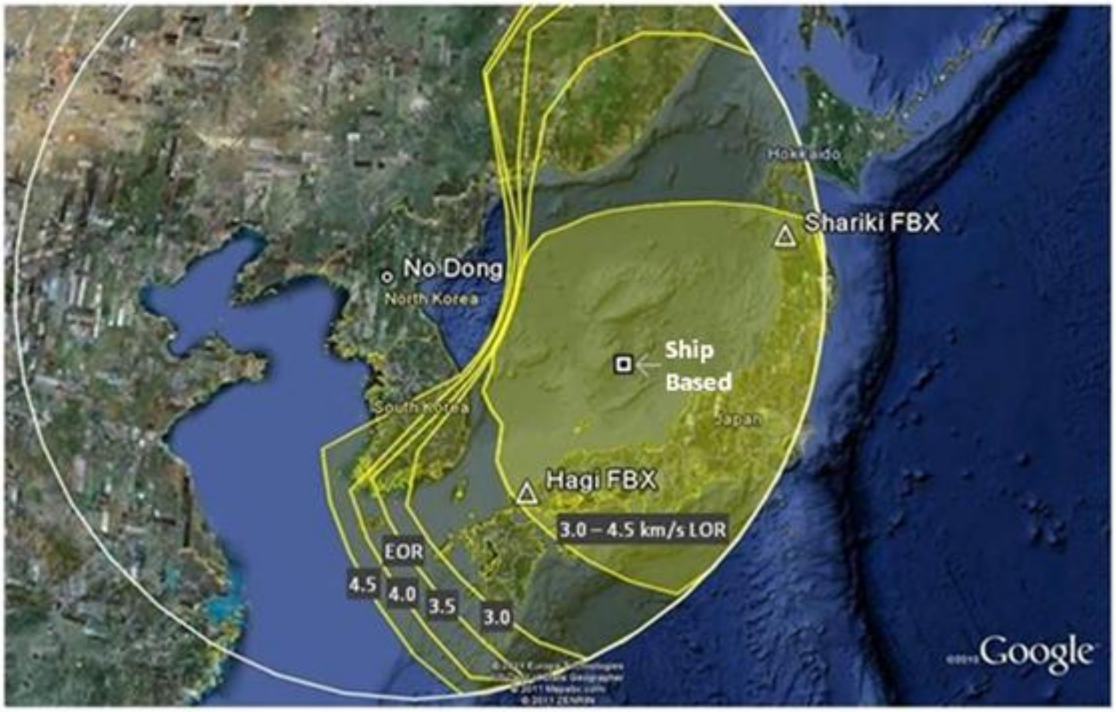

FIGURE 3-11 Notional ship-based single-shot LOR coverage of Japan: minimum energy MRBM trajectories. Note Hagi FBX location is notional.

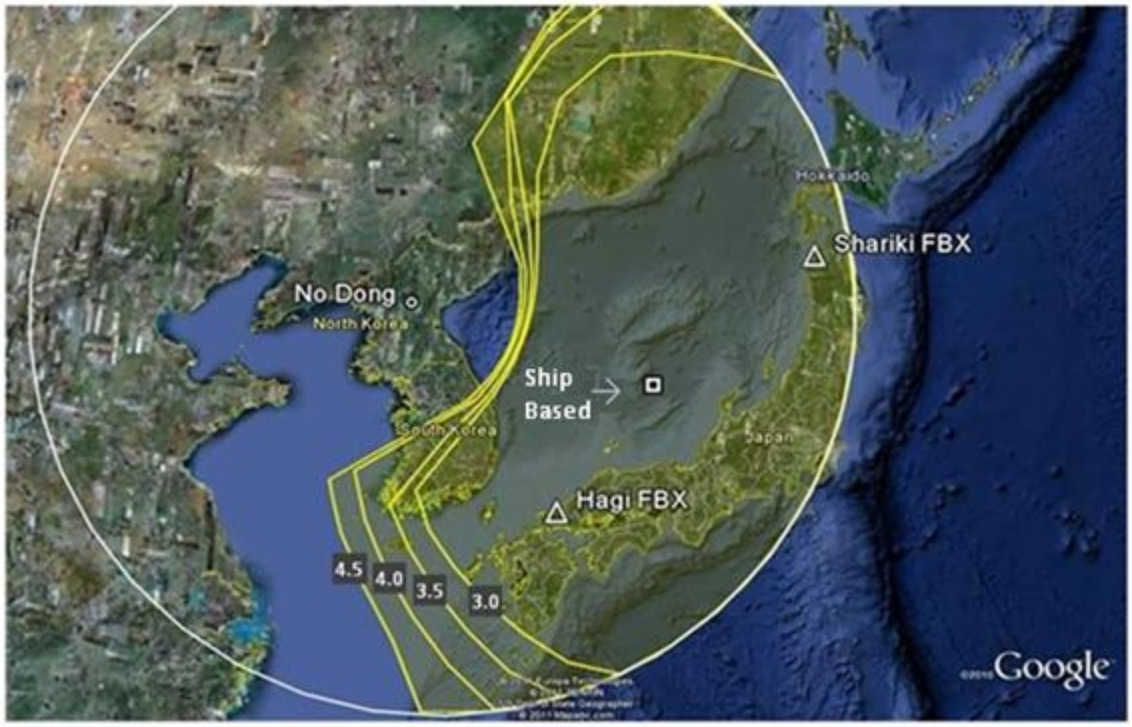

FIGURE 3-12 Notional ship-based single-shot EOR coverage of Japan: lofted MRBM trajectories. Note Hagi FBX location is notional.

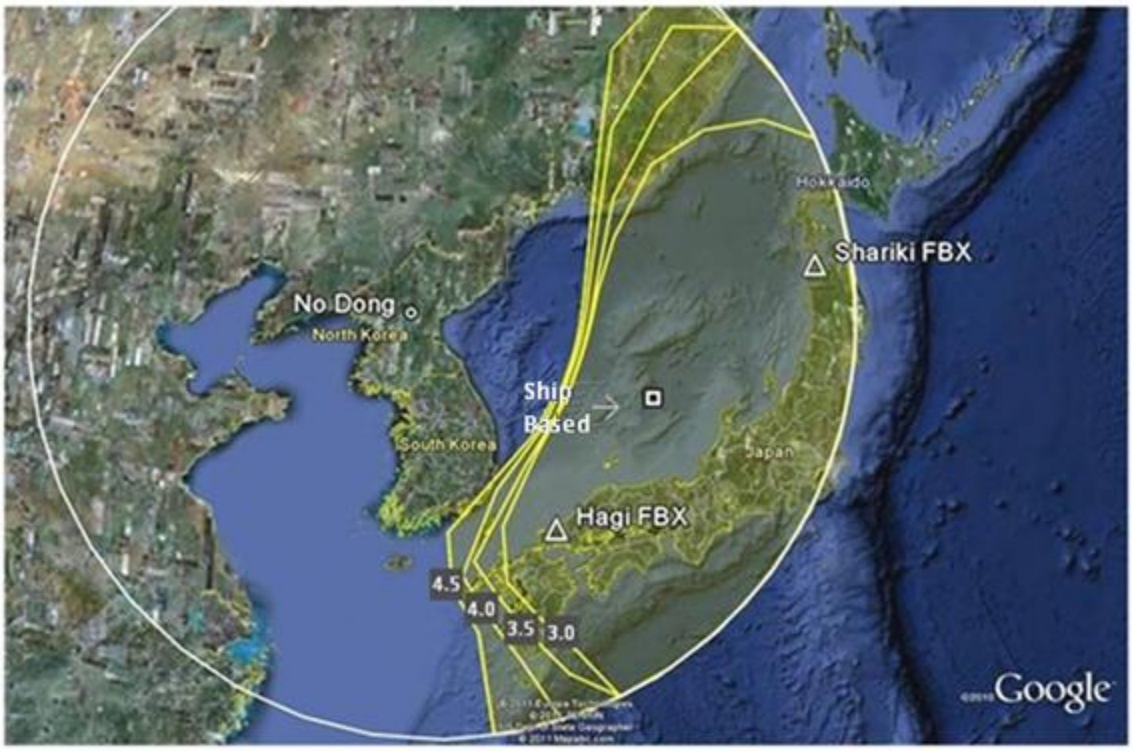

FIGURE 3-13 Notional ship-based single-shot EOR coverage of Japan: depressed MRBM trajectories. Note Hagi FBX location is notional.

A shoot-look-shoot firing doctrine utilizing EOR to obtain better defense performance yields the footprints shown in Figures 3-14, 3-15, and 3-16, again assuming that a second TPY-2 radar located near Hagi is deployed for the defense of Japan. These SLS EOR footprints shrink relative to the single-shot footprints because less time is available for the second shot. Still, only two, or perhaps three, sites are required to cover all of Japan for minimum energy and lofted trajectories. Depressed trajectories become somewhat more problematic, with at least three sites required to cover all of Japan. Therefore, SLS EOR coverage for the entire country can be provided from two or three ship-based locations in the Sea of Japan using at least two forward-based TPY-2 radars far apart on Honshu. A THAAD underlay defense can provide additional protection if desired. This should provide an effective defense of Japan against North Korean MRBMs for the foreseeable future.

Interceptor speed is not as crucial for the defense of Japan as it is for Europe, because the threat missiles are shorter range and have lower apogees. The shorter distance between North Korea and Japan means that threat missile detection can occur shortly after burnout, with accurate track data provided by two TPY-2 radars throughout the battle space. Nor is EOR as essential as in Europe, because the intercept ranges against North Korean MRBM threats directed against Japan are shorter and hence more compatible with the Aegis radar tracking capability. Hence, offboard sensors are less critical for footprint coverage.

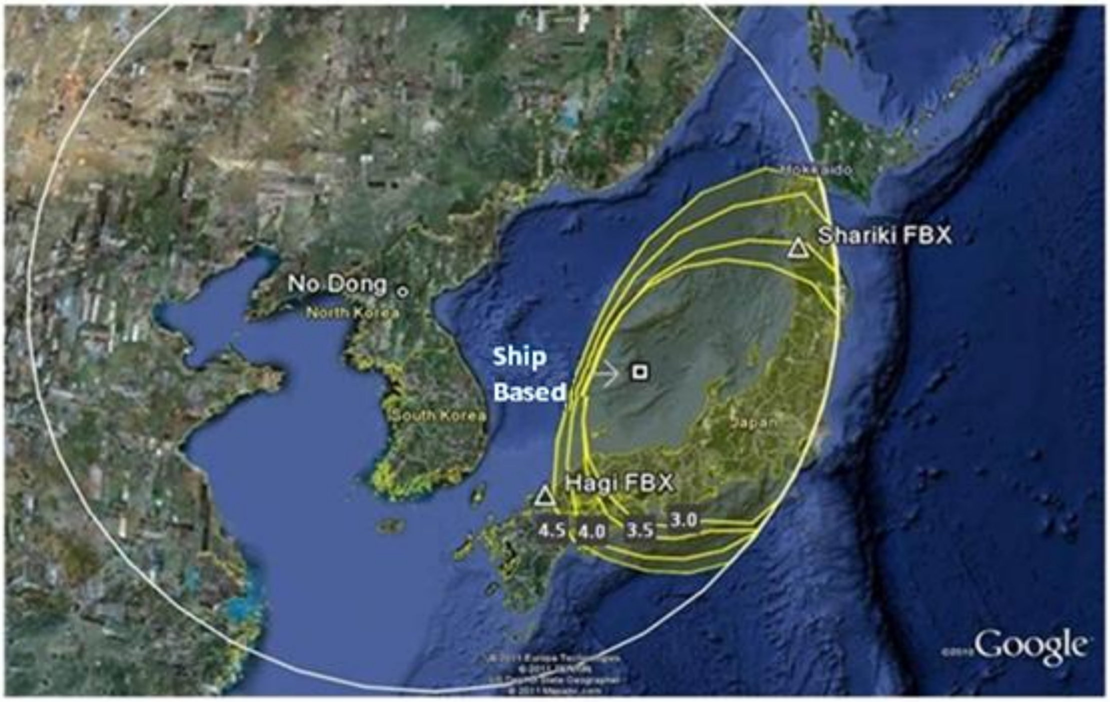

FIGURE 3-14 Notional ship-based SLS EOR coverage of Japan: minimum energy MRBM trajectories. Note Hagi FBX location is notional.

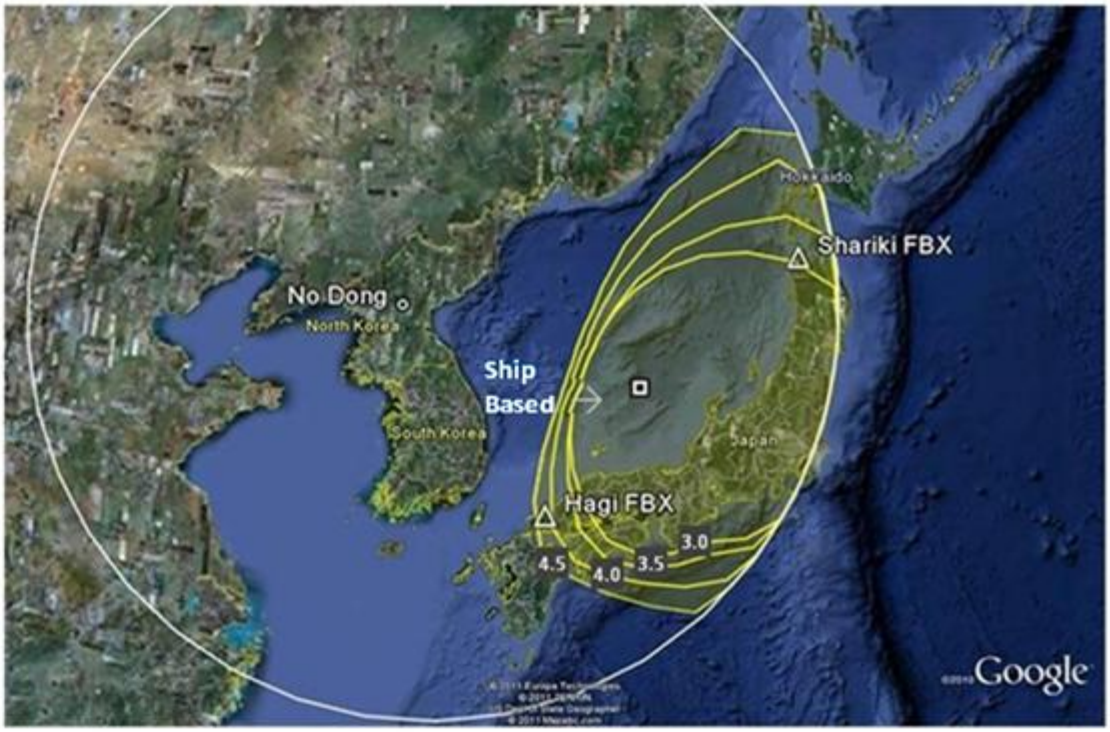

FIGURE 3-15 Notional ship-based SLS EOR coverage of Japan: lofted MRBM trajectories. Note Hagi FBX location is notional.

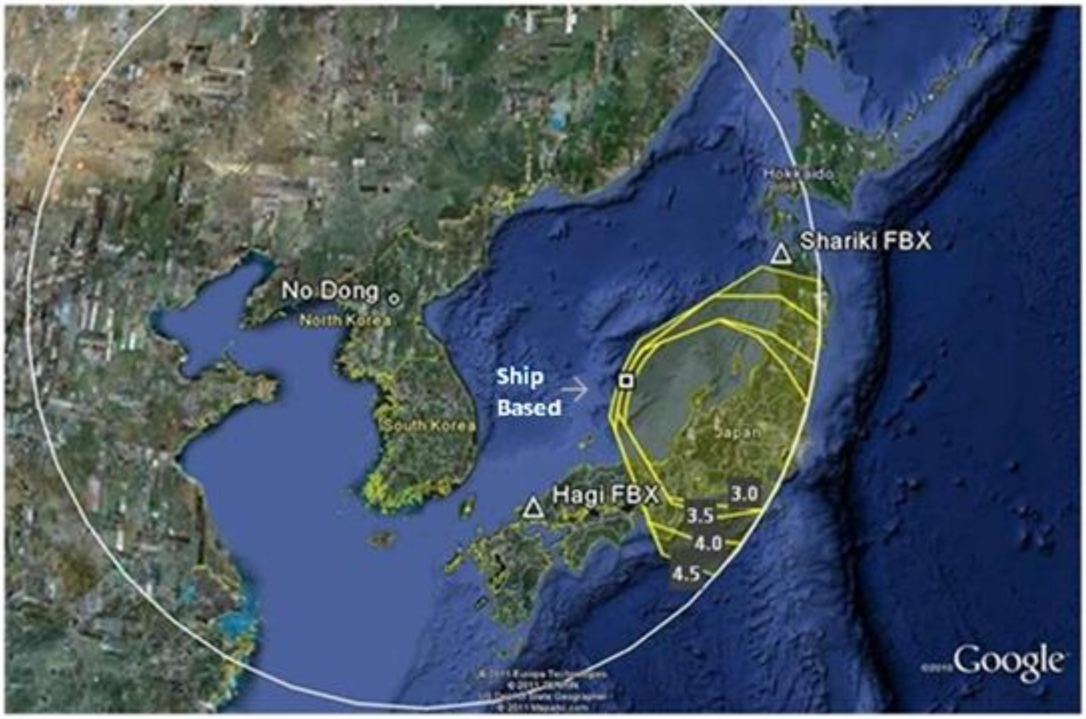

FIGURE 3-16 Notional ship-based SLS EOR coverage of Japan: depressed MRBM trajectories. Note Hagi FBX location is notional.

South Korea and Western Pacific Defense Analysis

Defense of South Korea against North Korean SRBM and cruise missile threats was not analyzed in any detail in this study, but because of the short burn times, low apogees and short total flight time appear to be best provided by a combination of PAC-3 and THAAD batteries located in-country. Because North and South Korea are so close, long-range artillery is also a major threat but was not considered in the study.

Defense of forward bases at Guam (about 3,500 km from North Korea) and Okinawa (about 1,500 km from North Korea) are essentially point targets that, like Hawaii, are each best defended by local offshore Aegis ships working in conjunction with a THAAD battery ashore. The THAAD AN/TPY2 radar provides LOR or EOR data to the Aegis system for the first shot and the THAAD battery provides a second shot. This approach is discussed in the classified Appendix J, where the defense of Hawaii is examined.

In addition, TPY-2 type XBRs located in Japan and Guam coupled with the Aegis higher performance interceptors located on or near Guam can provide SLS coverage of the entire island of Guam and an area of about 1,000 km diameter around and to the south and east of Guam against a typical MRBM threat, as shown in Figure 3-17. The blue contour line shows the SLS coverage footprint and the orange contour shows the single-shot kinematic coverage limit against a typical minimum energy North Korean MRBM. Additionally, the use of THAAD for the defense of Guam would be an excellent complement to Aegis coverage.

In summary, if also introduced as upgrades in the western Pacific along with THAAD, the Aegis evolutions currently being considered for the first three phases of the European PAA would provide the flexibility for defense of allies and forward bases against threats from North Korea or any other countries, limited only by the number of assets procured and deployed in the region.

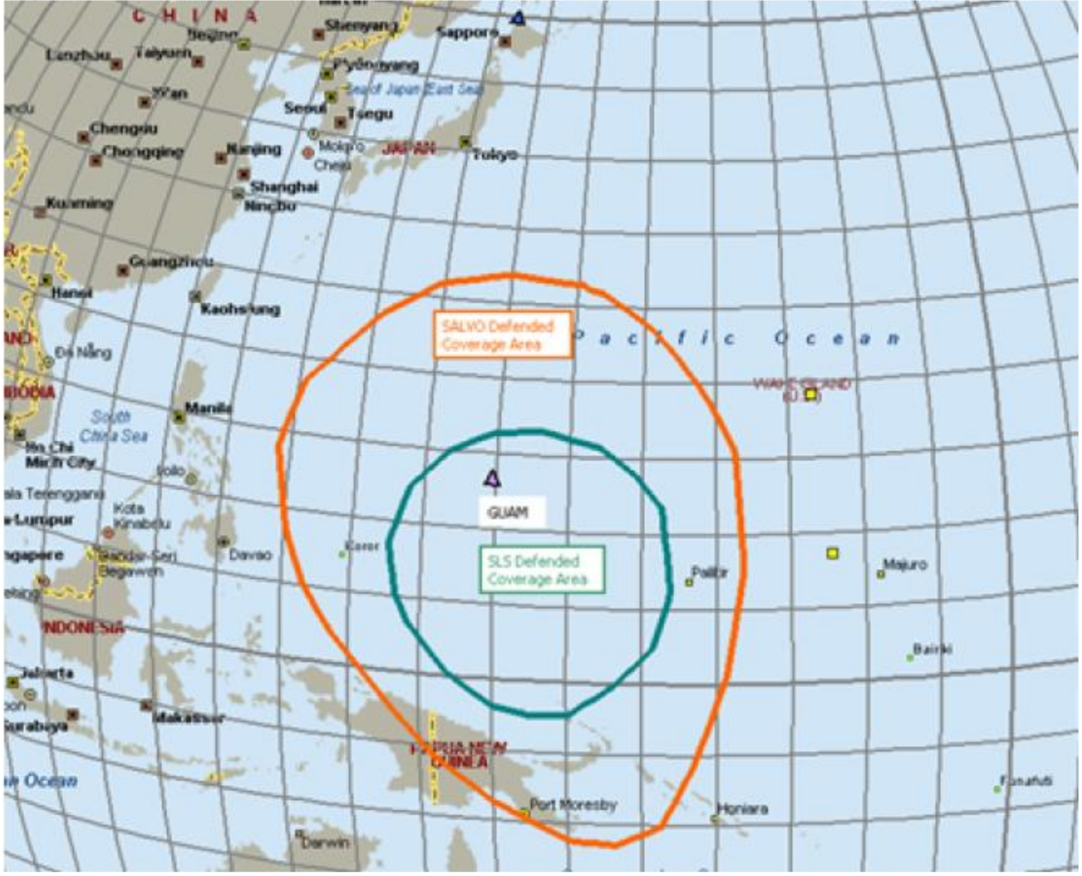

FIGURE 3-17 Defended area coverage footprint against a North Korean MRBM threat.

FINDINGS

Midcourse Discrimination

As discussed in Chapter 2, the formidable difficulties in being able to maintain boost-phase interceptors in the necessary locations to enable defense even against long-range attacks means that any operationally feasible defense against such attacks would have to effect intercept after the boost phase is complete. While terminal defenses might serve as a useful backup protection for extremely high value (or limited area) assets, the footprint limitations of terminal defenses mean that an effective defense will usually have to occur during midcourse. In short, there is no practical missile defense system that can avoid the need for midcourse discrimination, and the midcourse discrimination problem must be addressed far more seriously if reasonable confidence is to be achieved.

Exoatmospheric discrimination, by definition, requires identifying the threatening reentry vehicle (RV) from among the cluster of other nonthreatening objects that will be visible to the defense's sensors after the end of powered flight. Initially the nonthreatening objects may be unintentional—for example, spent upper stages, deployment or attitude control modules, separation debris, debris from unburned fuel, insulation, and other components from the booster, and the like. However, as threat sophistication increases, the defense is likely to have to deal with purposeful countermeasures—decoys and other penetration aids and tactics like salvo launches and antisimulation devices—that adversaries will have deliberately designed to frustrate U.S. defenses.

Evaluating discrimination effectiveness is an uncertain business. One should avoid overstating the ease that countermeasures that are theoretically possible can actually be made to work in practice, especially against advanced discrimination techniques using multiple phenomenologies from multiple sensors and exploiting the long observation time that midcourse intercept makes possible. It is perhaps noteworthy that the experience of the United States and the United Kingdom with the development of high-confidence penetration aids during the Cold War was a mixed success. It would be difficult for an adversary to have confidence in countermeasures without extensive testing, which the United States might be able to observe and on which it might gather data that would permit defeating the countermeasures.

Decoys are not, of course, the only countermeasures a midcourse defense system must face. Other possible measures to defeat defenses include maneuvering in midcourse and structured attacks involving simultaneous launches and/or attacks on key components of the defense, notably its sensors. As the threat evolves, defenses must adapt to these potential measures as well as to increasingly sophisticated decoy-type countermeasures. The art of midcourse discrimination, developed over many decades, does not provide perfect selection of RVs, but by designing a BMD architecture based on the capabilities described in this report, an adequate level of discrimination performance can be achieved in the near term and can give the United States a reasonable chance of keeping itself generally ahead in the contest between countermeasures and counter-countermeasures.[12] The committee believes that the best approach for addressing the midcourse discrimination problem is the synergy between X-band radar observations and onboard optical sensors with a proper SLS operational concept and firing doctrine, as described below. Midcourse discrimination is discussed in greater detail in Chapter 5 as well as in the classified Appendix J).

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[12] There is no unequivocal answer to the question of whether a missile defense can work against countermeasures. It depends on the resources expended by the offense and the defense and the knowledge each has of the other's systems. Thus, defense effectiveness against countermeasures inevitably will vary with time as the offense-defense competition unfolds.

Major Finding 3: There is no practical missile defense concept or system operating before terminal phase for either the U.S. homeland or allies that does not depend on some level of midcourse discrimination, even in the absence of deliberate decoys or other countermeasures. The only alternative is to engage all credible threat objects (the Multiple Kill Vehicle program was such a hedge). Therefore it is important to face the problem of midcourse discrimination squarely and to maximize the probability of accomplishing it.

- Initially the nonthreatening objects may be "unintentional"—for example, spent upper stages, deployment modules or attitude control modules, separation debris, debris from unburned fuel, insulation, and other parts of the booster. However, as threat sophistication increases, the defense is likely to have to deal with purposeful countermeasures—decoys and other penetration aids and tactics including salvo launches and antisimulation devices—that adversaries will have deliberately designed to frustrate U.S. defenses.
- The midcourse discrimination problem must be addressed far more seriously if reasonable confidence is to be achieved.

Major Finding 4: The synergy between X-band radar observations and concurrent optical sensor observations on board a properly designed interceptor (which could be a modified ground-based interceptor) closing on the target complex has not been exploited. The committee believes a combination of a proper operational concept and firing doctrine taking advantage of the battle space available for SLS offers the greatest potential for effective discrimination in the face of potential future countermeasures. Although it is by no means a certain solution, the committee believes this approach is not adequately exploited in current U.S. midcourse defense systems (such as GMD) and needs to be if the United States is to have an effective defense against limited attacks.

- The importance of this three-way synergy—X-band radar observations concurrent with optical sensor observations on board a properly designed interceptor together with SLS capability—cannot be overemphasized.
- This will require implementing a more realistic and robust program to gather data from flight tests and experiments (including on flights of U.S. missiles) from the full range of sensors, and making full use of the extensive data collected from past experiments to continue developing the applied science from which robust discrimination techniques and algorithms can be developed.

Major Finding 5: Based on information presented to the committee, it does not appear that MDA takes into account how the signatures of various threat objects behave when observed *concurrently* for several hundred seconds by both interceptor-mounted optical sensors closing on the threat complex and X-band radar measurements. Moreover, it appears that virtually all of the effective analytical work at MDA in optical signatures was terminated several years ago, ostensibly for budget reasons. The Midcourse Space Experiment (MSX) and the High-Altitude Observatory 2 (HALO-2) programs, for example, provided significant amounts of useful data. Yet the committee could not find anyone at MDA who could show it those data or explain them let alone the data from ground-based interceptor flight tests.

- Forty years of optical signature data from well-instrumented past and recent flight tests are lying fallow and unanalyzed with respect to current technological capabilities. These include programs with acronyms such as designating optical tracker (DOT), fly-along infrared (FAIR), the Homing Overlay Experiment (HOE), the Queen Match Discrimination Experiment, and others.

- While radar and optical midcourse discrimination technologies have been pursued for years, they have largely been on separate tracks and more in competition than in collaboration.

Homeland Defense

The GMD system at FGA and VAFB was deployed before its development was complete in order to meet what was considered an urgent need to get a system deployed quickly. As a result, GMD could not benefit from a normal development cycle, and it evolved in an environment of changing requirements, with the end result that it is limited in its ability to perform the U.S. homeland defense mission.

The current GMD architecture does not take advantage of technically available means of discrimination or of effective engagement doctrine, but it could be modified to do so. Its shortcomings are not limited to concerns about discrimination. The GMD interceptors are very expensive ($70 million to $86 million FY 2010 dollars) even in comparison with other non-BMD weapon systems of comparable size and complexity. To the extent the firing doctrine for GMD would rely on firing salvos the expense can be even greater. Other limitations in the current GMD system are discussed in the classified Appendix J.

Significant but feasible and affordable upgrades are needed to the GMD system and its configuration and supporting facilities if it is to be genuinely capable of its stated mission of protecting all of the U.S. homeland against the sort of long-range missile attack that North Korea and Iran may be able to mount in the next decade or so if they press their development programs forward. Specific upgrades are provided in Chapter 5.

Major Finding 6: To be credible and effective, any ballistic missile defense system must be robust even if any of its elements fail to work as planned, whether that failure is due to a failure of discrimination or to something else. Moreover, a properly configured midcourse defense is the most cost effective and resilient method of defending the U.S. homeland against ballistic missile attack. What is needed is a system that is resilient to failure, in particular the failure to discriminate successfully. This implies making use of SLS doctrine that exploits the potential battle space. The committee has analyzed the effectiveness of the discrimination capability of the GMD system and finds that the system can, if it works as designed, deal successfully with the initial threats from North Korea. However, the current GMD system has been developed in an environment of limited objectives (e.g., dealing with an early-generation North Korean threat of very limited numbers and capability) and under conditions where a high value was placed on getting some defense fielded as quickly as possible, even if its capability was limited and the system less than fully tested. As a result, the GMD interceptors, architecture, and doctrine have shortcomings that limit their effectiveness against even modestly improved threats and threats from players other than North Korea. Nevertheless, 30 GMD interceptors exist (or soon will), and they and their support network of sensors—including additional properly chosen and located and already fully developed ground-based forward X-band radar elements—and communications could, at an affordable cost and on a timeline consistent with the expected threat, be modified, emplaced, and employed so as to be far more effective for the homeland defense mission.

- The foundation work for these modifications has already been done by MDA.
- For example, GMD interceptors require a Block II ground-based interceptor incorporating KEI-like booster technology having a shorter burn time and a new kill

vehicle with talk-back capability to permit using downlinked information from a closing kill vehicle.

Defense of Deployed Forces, U.S. Allies, Partners, and Host Nations

The MDA and the Services appear to be on the right track for developing BMD systems for countering short-, medium-, and intermediate-range ballistic missile threats from rogue states to deployed forces and U.S. allies, partners, and host nations. However, while Aegis, THAAD, and PAC-3 are well developed and suited to their individual missions against these types of threats, there has been limited interface among them.

Major Finding 7: The Aegis ship-based SM-3 Block II interceptors with launch or engage on remote—both of which capabilities are under development—together with the THAAD and PAC-3 systems and their elements will provide, where appropriate, adequate coverage for defense of U.S. and allied deployed forces and of Asian allies.[13]

- With two or three Aegis ashore sites in Europe, that same combination can provide a layered late midcourse and high-altitude terminal defense for Europe.
- No interceptor with fly-out speeds less than or equal to 5.0 km/sec based in Poland or Romania or elsewhere in Europe can engage or interfere with Russia's nuclear deterrent ICBMs or submarine-launched ballistic missiles.
- Coverage of Israel and other Middle East areas against the anticipated threat will require additional Aegis and THAAD assets. (Turkey will require its separate defense using THAAD or the equivalent against shorter-range threats.) These requirements assume that single-shot defense of most areas is acceptable.
- Universal SLS capability, which is desirable for effective discrimination and other purposes, will require additional sites or terminal defense.

Major Finding 8: The first three phases of the European Phased Adaptive Approach (PAA) are expected to provide defense for Europe against a limited ballistic missile attack for deployed U.S. and allied forces within the region and the Middle East, provided the sensor architecture and the missile defense command and control (C2) center for the European PAA architecture can implement engage-on-remote capability.

- If modestly sophisticated countermeasures are anticipated for the IRBM threat, then the European PAA will need to include multiple X-band radar and long-range IR sensors (e.g., ABIR) that can provide concurrent data on IRBM trajectories similar to the countermeasures proposed for U.S. national missile defense. However, the IR data will need to come from external sensors because the SM-3 and THAAD kill vehicles have limited seeker range and limited divert capability. Fortunately, Aegis and THAAD are both capable of continuous communication between the kill vehicle and the C2 center.
- Europe can be covered with a SLS firing doctrine assuming enough sites are deployed, where the number of sites required depends on the interceptor speed—for

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[13] In the LOR concept, the engagement is controlled and in-flight target updates are provided from the launching ship. The Aegis program is also working to develop an EOR capability by 2015, whereby (1) the interceptor can be launched using any available target track and (2) engagement is controlled from and in-flight target updates can be provided to the interceptor missile from any Aegis AN/SPY-1 or AN/TYP-2 radar. The committee applauds the MDA's progress in achieving LOR capability for Aegis.

example, two or three sites would be required if the interceptor speed is greater than 5.0 km/sec.

- SLS, when combined with the sensor architecture and C2 center noted above, is expected to provide a relatively robust defense of Europe against a range of potential future countermeasures.
- Turkey, as a member of NATO, will require separate BMD elements to ensure its protection. THAAD is probably the most appropriate system for this purpose owing to the stand-alone capability of its X-band radar and its ability to intercept shorter range missiles.

Major Finding 8a: Phase IV of the European PAA may not be the best way to improve U.S. homeland defense.

- The speed of the Phase IV interceptor will need to be greater than can be achieved with a 21-inch missile to avoid being overflown by lofted ICBM trajectories from Iran if the interceptor is based in northern Europe (Poland).

4

Utility, Maturity, and Cost Effective Comparisons

Ballistic missile defense (BMD) is at a critical turning point if it is to meet the objectives set forth by the current and past administrations. As stated in Chapter 1, the title of this report, *Making Sense of Ballistic Missile Defense*, underscores three primary objectives in addressing the congressional tasking: (1) to provide a sound basis for resolving once and for all some of the claims for BMD systems, including sensors, which the committee found are possible in principle but are based on an unrealistically constrained view of the threat, or that given the kinematics and time constraints of the engagement problem, are not realistically achievable; (2) to independently assess, from a user's perspective, the effectiveness and utility of BMD systems being fielded as well as those being contemplated for future deployment; and (3) as chartered, to examine the resource requirements for each BMD system in relation to its mission utility. Here, the examination of resource requirements is based on currently available program cost data as well as historical cost data on systems with similar elements and considers the realities of achievable concepts of operations (CONOPS).

This report recommends a path forward for improved BMD effectiveness and cost avoidance. These recommendations include termination of some planned and ongoing BMD development activities, instead building on development work done to a level that gives confidence it can be successfully implemented in systems for the four missions examined in this report. If implemented, these recommendations can be accommodated within the current budget requested future years defense plan (FYDP) total obligational authority.

In the preceding chapters, an operational and technical assessment for U.S. boost-phase defense systems and non-boost alternatives is provided. In addition to the assessment of operational and technical elements called for in the congressional tasking, a detailed analysis of cost was also requested. This chapter summarizes the committee's comparison of operational utility, technical maturity, and cost for U.S. boost-phase and non-boost systems. It is important to note that the committee did not analyze personnel requirements for the force structure; however, the BMD system deployment recommendations for U.S. homeland and European defense are identified well enough to support further study of personnel levels. In general, the Services have defined the force structure and performance that they can afford for BMD missions requiring the use of Aegis, Terminal High-Altitude Area Defense (THAAD), and Patriot Advanced Capability (PAC)-3, and the committee does not believe an assessment of force structure and associated costs was part of its tasking.

COMPARISON OF BOOST-PHASE AND NON-BOOST-PHASE SYSTEMS

Twenty-Year Life-Cycle Costs

Figure 4-1 displays the 20-yr life-cycle costs (LCCs) for the BMD systems—U.S. boost-phase defense and non-boost-phase defense alternatives (midcourse, ascent, late midcourse, and terminal)—examined in this report from FY 2010 forward. Here, the total estimated costs (in FY

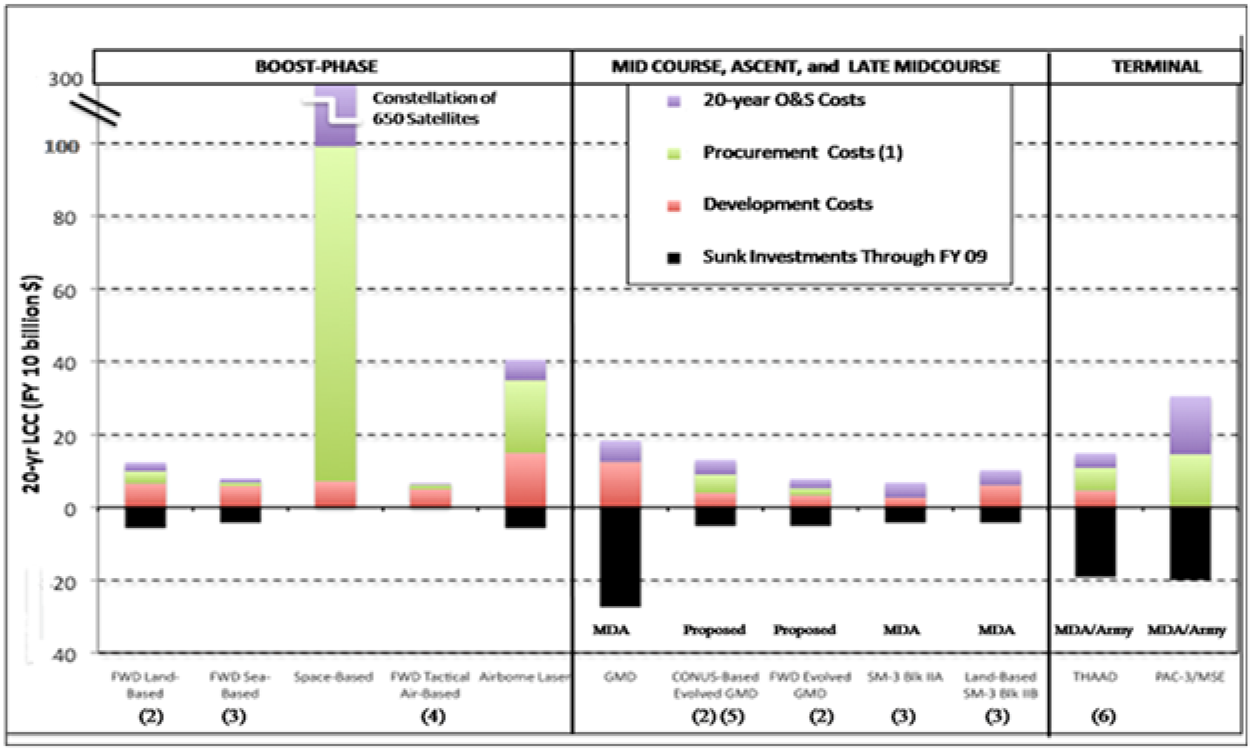

FIGURE 4-1 20-yr LCC for boost-phase and non-boost-phase alternatives. (1) Where applicable, MILCON costs included as part of procurement costs; (2) sunk investments based on kinetic energy interceptor heritage; (3) sunk investment based on Aegis block development upgrade, design, and production heritage of SM-2 Block IV; (4) CONOPS based on multimission use of retrofitted available F-15Cs and/or F-35s; (5) procurement cost includes MILCON estimates for recommended missile field and facilities infrastructure construction costs on new northeastern CONUS site; and (6) sunk investment cost for THAAD does not include separately identified past funds for AN/TPY-2 radar.

2010 constant-year dollars) are broken down into three categories: development; procurement, including military construction (MILCON); and operations and support (O&S) over 20 years. These costs do not include the cost of supporting sensors, which is provided in a later section of this chapter. Sunk investment costs from the start of these programs (or previous heritage programs) through FY 2009 for these various BMD systems are shown in black.

Comparison of Costs and Effectiveness

Table 4-1 and Table 4-2 compare the BMD systems examined in this report. Table 4-1 compares U.S. boost-phase defense systems and Table 4-2 compares non-boost-phase defense alternatives. The reader will recognize the programs of record discussed earlier in Chapters 2 and 3 but will also notice two other systems—continental U.S. (CONUS)-based evolved ground-based missile defense (GMD) (called GMD-E in Chapter 5) and forward-based evolved GMD—where the committee’s analysis and simulation work found significant weaknesses.

TABLE 4-1 Summary Comparison of Boost-Phase Defense Systems

	Potential Boost-Phase Defense Alternatives Kinetic Interceptors				
Potential Mission Applicability	Forward Land- or Sea-Based		Space-Based	Forward Tactical Air- Based	Airborne Laser
Operational utility	🟧		🟥	🟨	🟥
Applicable engagement resilience	🟧 Sensitive to basing, geography, and decision time. Cannot engage missiles that burn out earlier and at lower altitude.		🟧 Poor against salvo and unable to engage shorter-range missiles that burn out sooner and at lower altitude	🟧 Good only at close range after air superiority	🟧 Limited by geography, atmosphere, and fuel
Resilience to tactics and countermeasures	🟧 Sensitive to threat, short burn time, and altitude		🟧 Brittle to threat, burn time, altitude, and salvoing	🟧	🟨 Medium
Technology maturity	🟨		🟥	🟧	🟥
System LCC (FY 2010 billion $)	Land-based Sea-based	11-13.8 [a] 7-8.9[b]	187-311[c]	4-7.1[d]	30-43[e]
Force quantity buys	Land-based	Total of 34 = 20 + 10 test KEIs + 4 spares at two locations with 5 launchers +1 C2BMC per site	650 SBIs constellatioin size for boost phase of liquids + midcourse with v_{bo} = 5 km/sec and 20-cm optics	4 F-15C CAPs = 12 F-15Cs + 120 missiles (upper bound use of F-35s)	9 aircraft

NOTE: CAP, combat air patrol; CG, U.S. Coast Guard; DDG, guided missile destroyer. Color key: blue, system is highly effective; light green, system is effective for most but not all expected threats; yellow, system provides some capability but unclear how much can be achieved; orange, system provides marginal capability with serious questions about feasibility; and red, system not viable.

[a] Estimates based on leveraging the terminated KEI program and sunk research, development, testing, and evaluation (RDT&E) investment costs from FY 2002 with a 10-month study followed in FY 2003 by development effort through FY 2009. Remaining efforts require continuing booster live-fire testing; completing the design of the kill vehicle (KV) or multiple KVs (MKVs), interceptor integration and testing (I&T), and overall system I&T with mobile launcher with canister; command, control battle management, and communications (C2BMC)/fire control unit (FCU) system development and demonstration (SDD) phase span time estimated for another 4 to 7 years before production go-ahead.

[b] Estimates based on Aegis SM-2 Block IV. Assumed development cost and procurement (FY 2006 through FY 2010) and fuze and autopilot modifications and installation on 18 ships beginning in FY 2008 through FY 2011 as sunk RDT&E investment costs. Development cost only for bringing interceptor production restart and tooling and for incorporating potential design changes due to parts obsolense. SOURCE: Missile Defense Agency. 2008. “Aegis Ballistic Missile Defense Status, Integration, and Interoperability,” May 6.

[c] LCC estimate updated using higher costs to account for developmental testing/independent operation testing and evaluation (DT/IOT&E) testing prior to production and launch of space-based interceptors (SBIs) and the added quantity buy for both on-orbit spares to reach full operational capability (FOC) and SBIs needed for replacing those expended as part of continuous testing after FOC of one test per year for first 5 years and once every 2 years after that to ensure C2BMC operational readiness.

[d] USAF/MDA estimated marginal O&S cost for multimission role and assumed USAF invests in F-15C service life extension.

[e] Based on Congressional Budget Office, 2007, estimate of force of nine modified 747s to reach FOC.

TABLE 4-2 Summary Comparison of Non-Boost-Phase Defense Systems

	Potential Non-Boost Phase Defense Alternative						
	Midcourse		Ascent and Late Midcourse			Terminal Underlay	
Potential Mission Applicability	GMD	CONUS-Based Evolved GMD	Forward-Based Evolved GMD	Improved Aegis: SM-3 Block IIA	Improved Aegis: Land-Based SM-3 Block IIB	THAAD	PAC-3/MSE
Operational utility	🟨	🟦	🟦	🟩	🟩	🟦 Can engage up to IRBMs	🟨 SRBMs and cruise missiles
Applicable engagement relience	🟧 Brittle	🟦 Very resilient	🟦 Very resilient	🟩 With EOR	🟩 With EOR	🟦	🟦
Resilience to tactics and countermeasures	🟧	🟦	🟦	🟩	🟩	🟩	🟩
Technology maturity	🟩	🟩	🟩	🟩	🟨	🟦	🟦
System LCC (FY 2010 billion $)	16.4-20.3[a]	17-23[c]	6.4-9.2[d]	6.0-7.5[e]	9.2-11.5[g,h,i]	13.8-16.0[j]	25.6-33.5
Force quantity buys	Remaining buy of 12 GBIs through FY 2016 to achieve operational quantity of 30[b]	1 NE CONUS site with total of 50 operational interceptors + test assets (with 30 at new NE site + 20 at FGA	1 land-based site in Europe	Projected SM-3 Block IIA quantity 48 (2 dedicated Aegis ships or 2 Aegis Ashore land sites with 24 per site)[f]	Projected SM-2 Block IIB quantity = 24 (1 dedicated European land site)	9 batteries, buy quantity = 471 to 527 missiles	Remaining buy pf 275 {AC-3s + 1,528 new MSEs

Color key: blue, system is highly effective; light green, system is effective for most but not all expected threats; yellow, system provides some capability but unclear how much can be achieved; and orange, system provides marginal capability with serious questions about feasibility.

NOTE: MSE, missile segment enhancement (improved PAC-3); NE, northeast; QTY, quantity.

[a] Assumed GMD is the committee's baseline for midcourse, so development and procurement (not separated by MDA) includes RDT&E total investment cost (less sustainment) since national missile defense and total GBI.

[b] Total force quantity buy of interceptors through FY 2016 at FGA and VAFB. Procured 40 GBIs through FY 2011, and MDA budget in FY 2012 FYDP requested the addition of 12 GBIs—1 upgraded fielded GBI and 11 new ones (GBIs 34 through 44) before FY 2016.

[c] Silo-based evolved GMD includes development, procurement (including MILCON), and 20-yr O&S cost for NE missile field site and four new ground-based X-band (GBX) radars.

[d] Used THAAD battery O&S cost (less TPY-2 radar) as analog for evolved GMD battery sustainment costs after adjusting for differences in number of interceptors, launchers, and other system elements per battery.

[e] Based on the SM-3 Block IIA codevelopment and Aegis ashore RDT&E budget from FY 2010 thru FY 2016 and buy quantity of 29 and the estimated procurement budget cost of additional buy of 15 SM-3 Block IIAs.

[f] SM-3 Block IIA estimated procurement cost is based on a force quantity buy of 48 operational missiles plus additional test missiles based on a mix of either two dedicated Aegis ships or two Aegis ashore land sites each with a 20-yr O&S cost estimate based on sustaining a level of 24 operationally available missiles.

[g] Based on total RDT&E, procurement, and MILCON budget from FY 2011 through FY 2016 for a land-based SM-3 Block IIB and a development cost estimate continuing out to at least FY 2019 and possibly out to the FY 2021 time frame.

[h] FY 2012 MDA PB identified MILCON for construction of land-based SM-3 launch facility in FY 2013 budget.

[i] The procurement cost estimate is based on a force level quantity of 24 land-based SM-3 Block IIB operational missiles plus additional test missiles located at one dedicated European fixed site. The O&S estimates are based on continuous O&S of 24 operationally available missiles at one Aegis land-based site over a 20-yr period.

[j] THAAD O&S cost includes Army sustainment estimate.

Table 4-1 and Table 4-2 present summary measures of effectiveness along with a range of system LCC estimates and force-level quantity buys. Each effectiveness category is a summation of many measures of effectiveness. The system LCC estimates are broken down and discussed further in Appendix E.[1] Factors included in engagement resilience are defended footprint, battle space for failure replacement and follow-up shots, shot opportunities, leakage and wastage for a fixed inventory, and engagement endurance. The operational utility rating is an assemblage of several measures of military utility, including requirements for supporting sensors and other assets; basing constraints and vulnerability to attack; persistence on station; deployment time and cost; and amenability for high-fidelity operational testing while deployed.

A color rating is provided for each BMD system in each of the effectiveness categories as well as cost. The color ratings are as follows: blue is highly effective; light green is effective at relatively low costs with some weaknesses or lack of ability to handle all expected threats; yellow provides some capability at relatively low costs but unclear how much can be achieved; orange is a marginal capability at relatively low to moderately high costs with serious questions about feasibility or affordability; and red denotes not viable for one reason or another along with relatively high costs.

The 20-yr LCCs for each system are shown in the fifth row across, and the breakdown of those costs for development, procurement, MILCON, and O&S are provided in Appendix E. These LCCs include the additional LCCs for the supporting sensors for the alternatives shown. A separate analysis of supporting sensors and their LCCs is provided later in this chapter.

The U.S. boost-phase defense systems examined in this report are kinetic terrestrial-based (both land and sea), space-based, and air-based. As discussed in Chapter 2, no U.S. boost-phase defense system that is land-, sea-, or air-based can defend against long-range missiles launched from central Iran, where they would be based to protect them from attack as the United States did with its land-based long-range missiles. While shorter range missiles might initially be based in northwest Iran to maximize their reach, they could not be easily intercepted during boost because they burn out sooner and at low altitude.

The land-based system of boost-phase defense is the now-terminated Kinetic Energy Interceptor (KEI) program discussed in Chapter 2, which was determined to be impractical. In short, KEI is impractical because it cannot reach boosting threats launched from the interior of the countries of interest with any realistic interceptor or basing. As noted in Chapter 2, unless they were based in China or Vladivostok, boost-phase interceptors could not achieve timely intercept of a threat based in northwest North Korea. The situation with respect to Iran is even worse. That this was not understood by those responsible for managing these systems raises questions about the systems analysis capability of the MDA and others.

Sea-based systems for boost-phase defense do not fare much better. By virtue of their ability to maintain station in international waters to the east of North Korea, they could engage some threats launched easterly toward Hawaii while maintaining sea room. While one might expect launches from North Korea toward Japan, approximately 1,300 km away, the boost phase for such missiles terminates at low altitude, making them very difficult to reach unless the interceptor speed is very high. For example, boost-phase interceptors launched from Aegis ships would have a difficult time meeting such speed requirements due to the volume constraints on the Aegis VLS system. Similarly, an Aegis-based boost phase interceptor would have difficulty reaching liquid- or solid-propellant ICBMs launched from North Korea (which must head in a north or northeasterly direction if targeting the United States) because of the lack of suitable waters from which to launch such interceptors. Larger ship-based interceptors similar to the KEI in performance were also examined, and it was found that these could not engage solid-propelled missile threats headed to North America with sufficient sea room to keep the launch platform itself from attack.

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[1] In addition, Appendix E provides a detailed discussion and analysis of the cost sytem methodology utlized for this study.

Space-based systems for boost-phase defense are not geographically constrained and have worldwide coverage within their inclined orbits. However, the number of satellites needed is governed by the laws governing orbital dynamics, as discussed in Chapter 2. The resulting high cost of placing a constellation of sufficient size in orbit is noted above, and, as Figure 4-1 illustrates, even the least ambitious capability costs an order of magnitude more to acquire and sustain than any other BMD system. Specifically, it is important to recognize the break in scale for the O&S costs of space-based boost-phase defense in Figure 4-1, which shows that O&S cost is twice the cost of acquiring such a system.

Finally, the operational and technical limitations of an airborne laser (ABL) system are discussed in Chapter 2. In short, because ABL's laser range is limited, it has little operational utility even if it is less expensive. Furthermore, the limitation of range is fundamental, and no incremental improvements to the laser will affect this limitation in any significant way.

Of the non-boost-phase defense systems shown in Table 4-2, the Aegis program appears to be well executed. While the SPY-1 shipboard radar limits the autonomous performance of a single vessel, the implementation of launch on remote (LOR) mitigates that problem. The SM-3 Block IIA missile—the first to use a 21-in. second-stage motor—is unlikely to meet the expectations for performance improvements vis-à-vis the Block IB, and that has led to the consideration of a possible larger diameter Block IIB, which is still in the trade-offs stage. PAC-3, THAAD, and Aegis are on track for providing defense capabilities for U.S. forces and allies outside Europe.[2] Moreover, THAAD and PAC-3 appear to also be well-executed programs although, as noted later, the medium extended air defense system (MEADS) acquisition radar is a good candidate for addition to the PAC-3 because it would allow the Patriot radar to concentrate on the fire control task. In addition, the THAAD's interceptor would perform better if it took greater advantage of its radar capability.

SENSOR COMPARISON

In examining the present and proposed U.S. BMD systems, it is important to compare the sensors needed to execute the four defense missions discussed in this report. Costs are provided below, followed by the values and limitations of sensors supporting BMD missions.

20-Year Life Cycle Costs

Like Figure 4-1, which showed the LCCs for boost and non-boost alternatives, Figure 4-2 shows the 20-yr LCCs for each of the sensor systems considered either in place or to be acquired for supporting the various BMD interceptors and alternatives. Sunk investment costs already incurred for each sensor or heritage sensor system through FY 2009 are shown below the black horizontal line in black.

Figure 4-2 displays two key messages. The first is that the United States has invested in and is continuing to spend a great deal of money on a space-based infrared system (SBIRS) constellation with the full operational capability to detect and track boosters and predict their impacts quite accurately. The second is that having spent or committed the money for acquiring and sustaining a constellation of SBIRS satellites for the next 20 years, we can buy and support all the recommended additional supporting sensors for all missions for less than the total LCC of the proposed PTSS, which, as will be discussed later, adds little if any value to support the real needs of missile defense. If PTSS is justified for another reason, that reason has not been shared with the committee.

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[2] For defending South Korea and even Guam, it was found that the boost-phase trajectories were so low that only a system like THAAD, with its high endo- and low exoatmospheric capability, based in South Korea might be able to engage hostile missiles during their boost phase. Here, ships with Aegis during the late midcourse phase or THADD during terminal phases are the best defense for Guam, Okinawa, and Japan because of proximity.

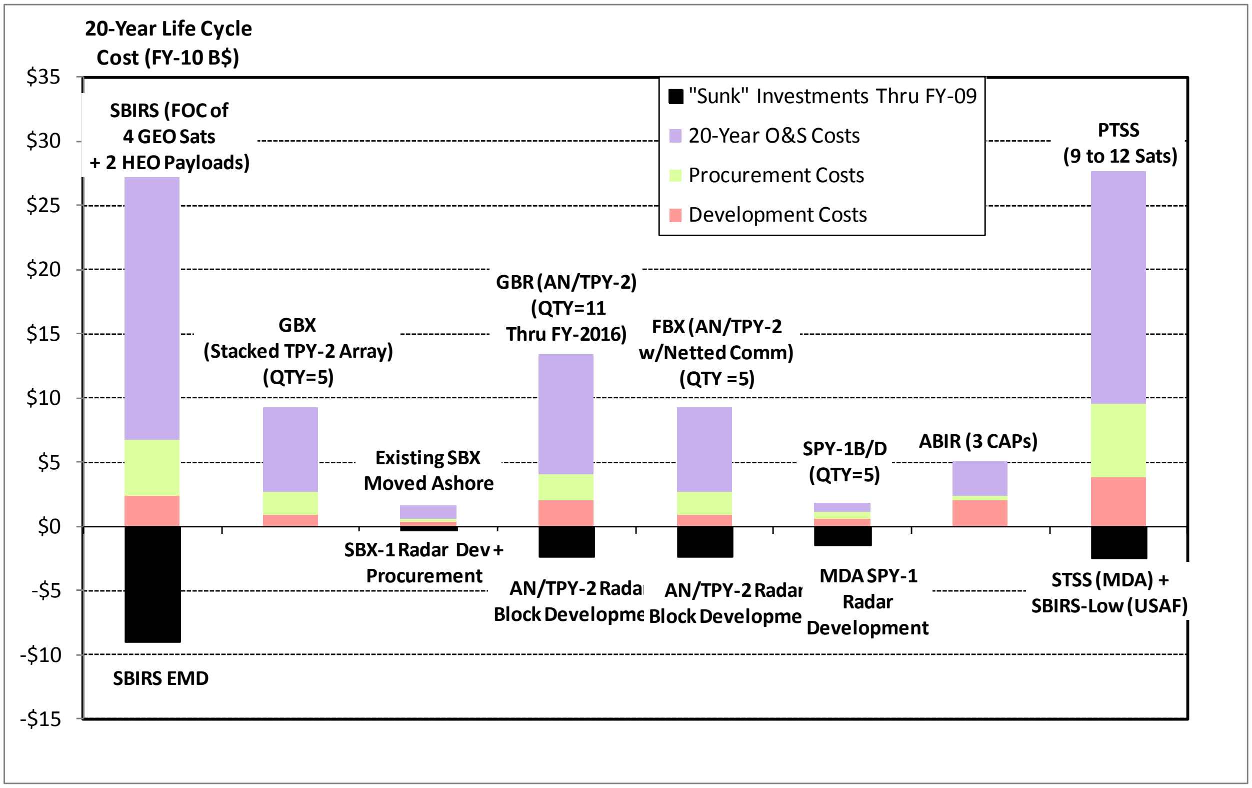

FIGURE 4-2 20-yr LCCs for sensors for U.S. boost-phase and non-boost phase alternatives. Note that (1) the 20-yr LCC estimate for SBIRS includes O&S costs of the replenishment GEO satellites and host satellites with HEO payloads and associated launches needed to sustain the 4 + 2 constellation with an average expected on-orbit life of 10 years per satellite; (2) the 20-yr LCC estimate for Precision Tracking and Surveillance System (PTSS) includes the O&S cost of the replenishment satellites and launches needed to sustain the constellation based on an average expected on-orbit life of 7 years per satellite. HEO, high Earth orbit; GEO, geostationary Earth orbit; GBX, ground-based X-band radar; STSS, space tracking and surveillance system.

With respect to the second message, it is important to note that SBIRS is a very important sensor suite for missile defense as well as for tactical warning and attack assessment. This successor to the Defense Support Program (DSP) is now partially operational, with two payloads on host satellites in highly elliptical orbit and the first GEO satellite, which was recently launched and is in position undergoing checkout. The second GEO is in ground checkout. These sensors have a greater frame rate than the venerable DSP satellites, which are nearing the end of their life.

SBIRS is important for almost all defense configurations because in most cases it is the first detector and tracker of a threat missile, particularly those launched from the interior of a country beyond the horizon of any radar. While its tracking precision requirement is based on strategic warning and assessment impact prediction, it is sufficient to cue other threat acquisition radars that are organic to defense systems. In fact the data are good enough to commit boost-phase interceptors where time is critical as well as robust midcourse interceptors, although, as will be shown, the committee recommends a second independent confirmation before the midcourse interceptors are committed. SBIRS also cues regional defenses to reduce the burden on their radar search capabilities, allowing radar resources to perform other intercept support functions.

The next section discusses the value and limitations of each of these existing or proposed sensors to support BMD in the various missions.

Value and Limitations of Sensors Supporting BMD Missions

X-Band Radars: FBX, GBR, GBX, SBX

Equally important for defense of CONUS and the phased adaptive defense deployment for Europe, the Middle East, and northeast Asia are the family of X-band radars that have been developed. Ground-based radar (GBR), developed for and organic to the THAAD system (in this case, AN/TPY-2), is being deployed in the Middle East as part of THAAD and also in stand-alone form, called the FBX. The AN/TPY-2 is a very powerful and versatile sensor not only for THAAD but also as a remote sensor to hand over track and discrimination data to other defense systems. The FBX, which is a THAAD radar with some additional communication for netting with other defense elements, is being deployed in Japan and is anticipated to be part of the European deployment.

The current early warning radars at Thule, Greenland; Clear, Alaska; and Fylingdales, United Kingdom, are lower bandwidth UHF radars that were developed and deployed during the Cold War and have been upgraded to varying degrees. They can detect ICBM threats but have limited ability to discern and track what is in a threat complex. The Pave Paws radars at Otis Air Force Base in Massachusetts and at Clear, Alaska, are designed more to detect and track submarine-launched ballistic missiles but are still limited in their ability to image. A third Pave Paws radar, at Beal Air Force Base, California, is still active and represents a large investment by MDA; however, it has very limited operational utility against intercontinental ballistic missiles (ICBMs) due to its location. While all these radars can be used to commit midcourse interceptors that have sufficient onboard sensing, autonomy, and divert capability to acquire and parse the threat complex during fly-out, they offer little help in discrimination of decoys or other countermeasures.

Accordingly, the GBX radars shown in Figure 4-2, which are X-band radars with longer range, should be placed at these locations (i.e., at Thule, Clear, Fylingdales, and Otis) and at Grand Forks, North Dakota, adjacent to the existing radar installations. To avoid the need for developing a new radar capable of detecting and tracking threat objects in excess of 3,000 km, it is recommended that (1) the SBX sea-based radar be moved to Adak, possibly placing that radar on its turntable ashore, and (2) a new variant we call “GBX”be created by stacking two TPY-2 radar arrays one on top of the other and integrating their coherent-beam-forming electronics and software to provide twice the power and twice the aperture X-band radar with a 120 degree by 90 degree field of view. These GBX radars mounted on azimuth turntables would be in fixed installations and would provide, in concert with existing TPY-2s and FBXs, almost continuous coverage of potential threats from North Korea to the United States or from Iran to the United States and Europe.

One of the benefits of this approach is that it takes advantage of the learning curve of transmit/receive modules, which are a large part of the cost of a radar. It does not, however, take advantage of any next-generation technological advances, which invariably raises the price of these devices.

S-Band Radar

The Aegis shipboard SPY-1 B/D S-band radar was designed as an air defense radar but also performs well against shorter range or large-cross-section ballistic missile threats provided it is cued from some forward sensor. Its value for both fleet defense and theater-level defense lies in its mobility and endurance on station. All current and projected SM-3 interceptors are capable of outreaching the ship’s radar yet depend on the radar for discrimination support, guidance updates, and two-way data flow. The radar is, however, limited by its frequency in midcourse discrimination capability. To get around the radar performance limitation against high-velocity small-cross-section threats, the Aegis system relies on cooperative engagement handovers from other up-range Aegis ships or another forward-based sensor such as a TPY-2. This is referred to as LOR capability, allowing an earlier interceptor launch against longer range threats.

Airborne Infrared

The airborne infrared (ABIR) sensor mounted on an unmanned aerial vehicle (UAV) is currently being evaluated for providing acquisition and track data for midcourse intercepts, presumably when there is no forward radar available. Two sensor platforms are required for stereo measurement. Because their range is limited by the altitude of the UAV, looking above the clouds and the IR-radiating atmosphere, the number required and their vulnerability become an issue. However, at least one version is being field tested. The rationale for this concept as presented to the committee was never made clear, particularly how just two sensors on station would deal with several missiles launched at short intervals. If a forward-based radar can also view the interceptor as it flies out, then it could take over a communication with the interceptor until its intercept is complete. This is known as engage on remote (EOR) and allows the interceptor to fly beyond the range of the SPY-1 radar.

Precision Tracking and Surveillance System

Finally, the PTSS is the latest in a series of supporting sensor systems proposed by MDA and its predecessors to provide midcourse tracking and discrimination to support missile defense constructs. These systems, which originated in the 1980s, included Brilliant Eyes, SBIRS low, the space tracking and surveillance system (STSS), and others and were aimed at making satellites in low Earth orbit responsible for tracking the threats and discriminating among the threat objects after their powered flight. The idea was to provide a very small target handover volume to an interceptor with a homing kinetic KV that could be small and would have limited onboard sensor, processing, and divert capability. Two experimental STSS prototypes were eventually built; they have been in orbit for 2 or 3 years and are reported to have successfully observed missile flights.

Conceptually, by putting more capable sensing and processing on a relatively small number of satellites rather than on a much larger number of interceptors, overall system costs could be reduced. The fewest satellites needed would be approximately 24 in inclined orbits, and even then the sensor ranges required for the concept to be effective were great, which made the discrimination problem more difficult.

The rationale for PTSS was never explained to the committee in any coherent way. It was said that SBIRS could not provide adequate cuing for defense radars, which does not jibe with what the committee knows about SBIRS capability. Moreover, PTSS was said to keep the objects in view for a long time, from before deployment throughout midcourse flight, providing midcourse discrimination even though it is generally too far away to do so and is limited to viewing above Earth's limb. The committee was told that the PTSS was a 9-ball equatorial constellation with a 7-yr life that has since grown to a 12-ball constellation. (The system is discussed in much greater detail in the classified Appendix J). The life of each satellite is now 5 years, which means that it will have to be replaced three times over the 20-yr period.[3] Here, the committee chose to use a cost in the middle of the range (see Appendix E).

As previously noted, one of the key messages in Figure 4-2 is the high cost of PTSS compared to the costs of the other supporting sensors for BMD—that is, having invested in acquiring and sustaining a constellation of SBIRS satellites for the next 20 years, or having

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[3] Also, in a 2011 Congressional Budget Office report entitled *Reducing the Deficit: Spending and Revenue Options*, it is stated that "Construction of replacement [PTSS] satellites would begin within the next decade if the design life of the PTSS satellite was less than seven years."

committed such an investment, the United States can buy and support all the recommended additional sensors for less than the total LCC of PTSS. Given these high costs, the utility of PTSS was analyzed in depth. The findings of this analysis are presented in the next section.

FINDING

PTSS appears to be a solution looking for a problem. It has been proposed that PTSS would provide detection and track data for early intercept by Aegis interceptors for fleet protection off Taiwan and for the phased adaptive European deployment. Unanswered is a question that could be politically sensitive—namely, why one or two THAAD battery radars on Taiwan would not provide better data, since in realistic CONOPS for that scenario, it is unlikely that any Aegis ships would venture close enough to effect an intercept in the ascent or early midcourse phase. Instead they would more likely be east of Taiwan with the rest of the fleet and would have to engage in late midcourse. While a cue will be needed for Aegis, a THAAD radar on Taiwan could acquire and track small cross-section targets much further away than the distance across the Taiwan (Formosa) Strait. This would seem a more logical, to say nothing of a much lower cost, solution. The Shariki, Japan, FBX radar provides a very accurate track of threats from North Korea to Hawaii and Alaska when propagated forward. Similarly, in Europe the FBX TPY-2 radar can provide a better cue, track, and discrimination capability than PTSS for the phased adaptive deployment of Aegis ashore.

The committee sympathizes with MDA’s desire for its own space-based observation capabilities, because until recently, the Air Force paid insufficient attention to the needs of missile defense in its space-based surveillance programs. Publicity surrounding the great success of STSS in observing birth-to-death flight of missiles notwithstanding, PTSS utility is very limited.

Moreover, setting aside its questionable utility, the proposed constellation is very expensive compared to other alternatives. To test this conclusion, an analysis was done of an ICBM launch out of North Korea toward Hawaii using only the FBX radar in Shariki, Japan, cued by SBIRS or DSP, to determine the handover volume propagated some 600 sec forward to acquisition by a GBX in Kauai with no other sensor help. This analysis is provided in classified Appendix K, and the results confirmed the committee’s view that even in this long-timeline case with minimal radar coverage, the forward-based FBX or THAAD radars together with the recommended version of GBX are adequate for any handover and provide significant support for midcourse discrimination, which PTSS cannot provide.

PTSS appears to have a more limited set of objectives: namely, it focuses on increasing the coverage of Aegis SM-3 interceptors by providing accurate and more continuous tracking of the threat objects during their midcourse flight. Presumably the stereo track accuracy from the satellites would be suitable for launching an interceptor from the Aegis ship or shore base well before its radar could acquire the target. Relayed in real time to the Aegis radar, these data could then be transmitted by the SPY-1 to the interceptor (LOR) or even by another radar (EOR) during its fly-out as part of its guidance function.

For the BMD missions examined in this report, the Aegis system plays an important role in defending deployed forces and allies and friends and in defending against a limited or accidental attack. The Aegis system also plays a limited role with respect to U.S. homeland defense, Hawaii in particular. In most of these roles, LOR or EOR will be important.

In the PTSS construct, the tracking data would come from stereo-optical data available from several of 12 satellites in equatorial medium altitude (1,500 km) orbit, 30 degrees apart in longitude. At last check, these satellites would be cued on where to look by some sensor, presumably SBIRS. These cold-body-tracking satellites must look above hard Earth and its limb for threats launched from various latitudes, from 31 degrees to about 41 degrees North. There is one exception, the antiaccess scenario around Taiwan, where threat trajectories could be at latitudes as low as 22 degrees North and visible for less time above Earth's limb.

Figure 4-3, Figure 4-4, and Figure 4-5 show several notional trajectories for threats fired from the Middle East to Western Europe as seen from three PTSS satellites at a single point in time.[4] While the satellites move about 90 degrees during the duration of these notional trajectories, there are always three of them viewing the notional trajectories from approximately these locations. Figure 4-3 is from a satellite passing above 0 degrees longitude (Greenwich meridian); Figure 4-4 is from a satellite passing above 30 degrees East longitude; and Figure 4-5 is from a satellite passing above 60 degrees East longitude. In short, all three satellites could see large portions of these notional trajectories above Earth's limb, with two of the three seeing the threats before burnout, and would be generally looking at targets at slant ranges 3,000 km to 7,500 km away, thus making the system's value for discrimination negligible (see classified Appendix J for greater detail).

Tracking and imaging of the threat from a cued, forward-based AN/TPY-2 X-band radar handed over to the suite of recommended X-band radars at the early warning radar sites provide excellent data on the size of the raids and also provide initial threat tracking discrimination data; they do this at an LCC between one third and one fourth the acquisition cost and the LCC of PTSS. While PTSS is a hedge against the inability to negotiate a forward site for this AN/TPY-2 radar, the value added by PTSS is very low and comes at a very high cost (see Appendix E and classified Appendix J for greater detail). For example, island areas, such as Hawaii, Okinawa, and Guam are best defended against missile attack by Aegis in late midcourse with a THAAD battery providing improved radar coverage and discrimination support and a second shot capability if warranted.

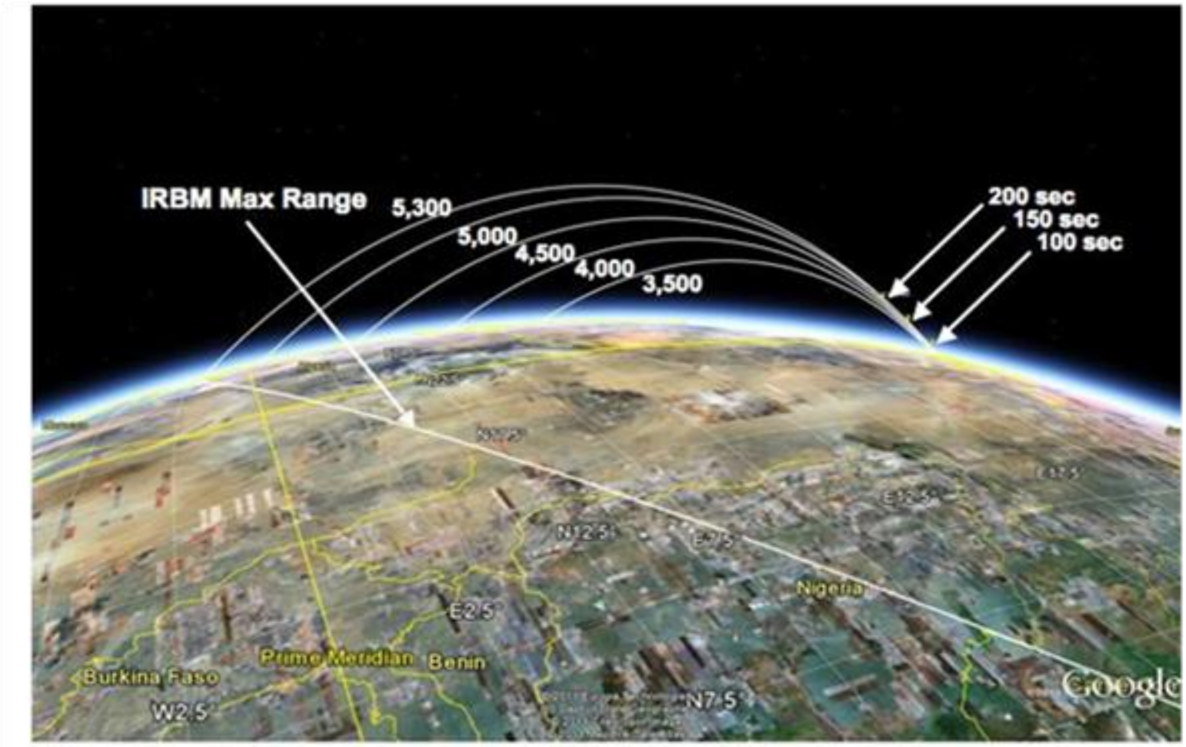

FIGURE 4-3 PTSS view of notional 5,600 km intermediate-range ballistic missile (IRBM) as the satellite passes over 0 degrees East.

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[4] Figures 4-3 to 4-5 were generated from the committee's analysis using Google Earth. ©2011 Google, Map Data©2011 Tele Atlas.

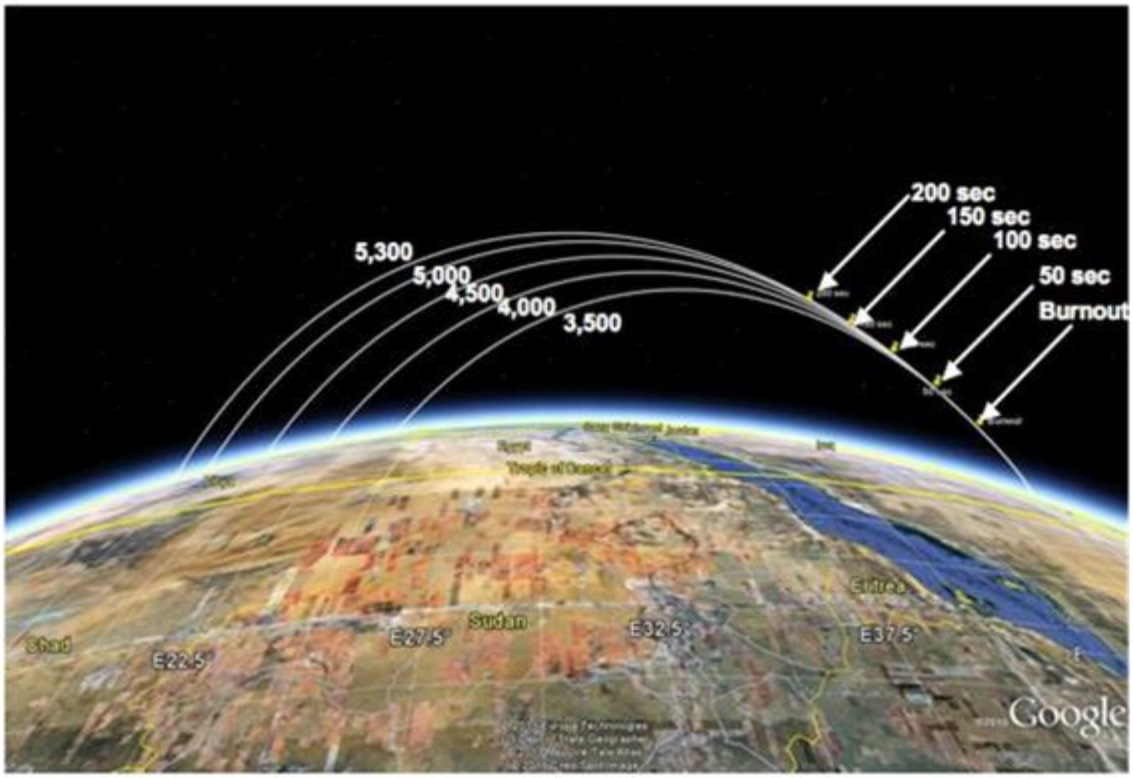

FIGURE 4-4 PTSS view of notional 5,600 km IRBM as the satellite passes over 30 degrees East.

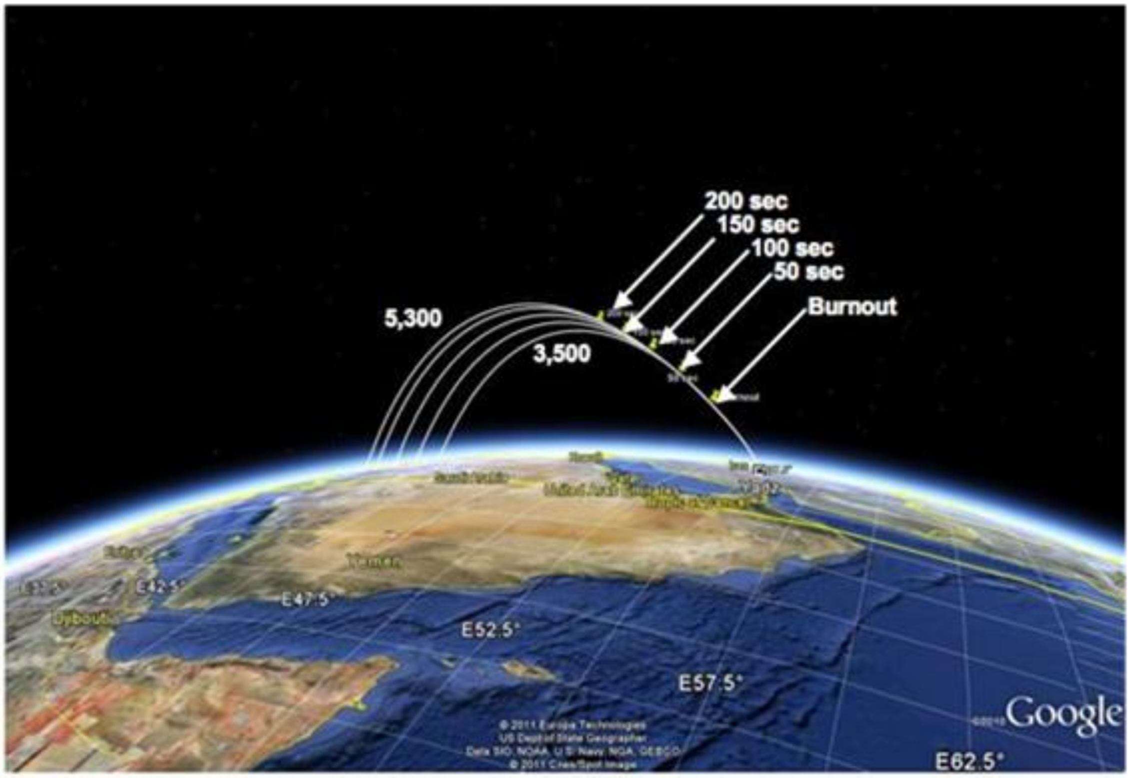

FIGURE 4-5 PTSS view of notional 5,600 km IRBM as the satellite passes over 60 degrees East.

Major Finding 9: The proposed Precision Tracking and Surveillance System (PTSS) does not appear to be justified in view of its estimated life-cycle cost versus its contribution to defense effectiveness. Specifically, the justification provided to the committee for developing this new space-based sensor system was questionable, and the committee's analysis shows that its objective can be better accomplished by deployment of forward-based X-band radars based on the Army Navy/transportable radar surveillance model 2 (AN/TPY-2) system design at much lower total-life-cycle cost.

- The AN/TPY-2 radar already developed for THAAD and already deployed can be exploited to provide the required capabilities for all foreseeable defense missions.
- Taking advantage of the existing manufacturing base and the learning curve as more units are built would be a very cost-effective way of supporting the recommendations in this report.

RECOMMENDATIONS

Boost-Phase Systems

Given the foregoing assessments of the feasibility of boost-phase defense and of system alternatives in light of the objectives of the U.S. administration with respect to providing ballistic missile defense capabilities both abroad and at home, it is evident that ballistic missile defense is at a critical turning point. To that end, this section of the report provides specific recommendations based on the committee's analysis and the findings in Chapters 2, 3, and 4. In short, the committee recommends that no more money be spent on boost-phase defense except for continued R&D on laser technologies that could be useful for other missile defense purposes. Indeed, the committee agrees with the termination of the KEI program and the transitioning of the ABL program to a test bed. The committee's assessment of the fragility and exceedingly high cost of space-based interceptors and of the relatively meager benefit of what they provide leads it to recommend that they not be considered further.

Major Recommendation 1: The Department of Defense should not invest any more money or resources in systems for boost-phase missile defense. Boost-phase missile defense is not practical or cost effective under real-world conditions for the foreseeable future.

- All boost-phase intercept (BPI) systems suffer from severe reach-versus-time-available constraints. This is true for kinetic kill interceptors launched from Earth's surface, from airborne platforms, or from space. It is also true for a directed-energy (laser) weapon in the form of the airborne laser (ABL), where the reach is limited by problems of propagating enough beam over long distances in the atmosphere and focusing it onto a small spot, even with full use of sophisticated adaptive optical techniques.
- While there may be special cases of a small country such as North Korea launching relatively slow burning liquid propellant ICBMs in which some boost-phase intercepts are possible, the required basing locations for interceptors are not likely to be politically acceptable.[5] This recommendation is not intended to preclude funding of generic research and development such as the ABL test bed, which is currently involved in boost-phase intercept, or funding of adaptive optics concepts or advances in high-power lasers that may be useful for other applications.

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[5] For example, while a North Korean ICBM aimed at Hawaii and some other Pacific locations could be intercepted in boost phase by a properly located Aegis ship, the United States cannot realistically or prudently expect that BPIs intended for defense against North Korean or Iranian attacks can be stationed in Russian or Chinese airspace or over other nonallied territory (or where overflights of such territory would be necessary to reach on-station locations), at least short of a full resolution of Russian and Chinese concerns about U.S. missile defense and agreement on extensive cooperation in such defense.

Recognizing that boost-phase defense is not practical or feasible for any of the missions that it was asked to consider, the committee believes it is important to examine the gain in effectiveness versus LCCs for non-boost-phase defense alternatives as they evolve over time. Figure 4-6 illustrates the evolutionary pathway of each non-boost-phase defense alternative for each of the four defense missions, what they buy in effectiveness, and the incremental LCC implications for pursuing each pathway. In this figure, there are two basic evolution pathways for the specified missions. The first path, starting at the left column—defense of U.S. deployed forces and host nations—is also applicable to defense of friends and allies. The second evolutionary path, which starts in column two, shows the alternatives for homeland defense.

For each of the four defense missions illustrated in Figure 4-6 (one, for instance, is "Homeland Defense Against Iran and Others"), the effectiveness of a particular non-boost-phase defense alternative is rated by color (see the key at the upper right of the figure); 20-yr LCCs are shown along the vertical axis. These costs include the cost of supporting sensors to reach and sustain the end state, represented by the points where the lines for each defense alternative terminate. They do not, however, include PTSS or ABIR being considered for later introduction into the PAA.[6] Figure 4-6 also displays the costs for each defense alternative from its inception (see data in "Sunk Costs" at the bottom of the figure).

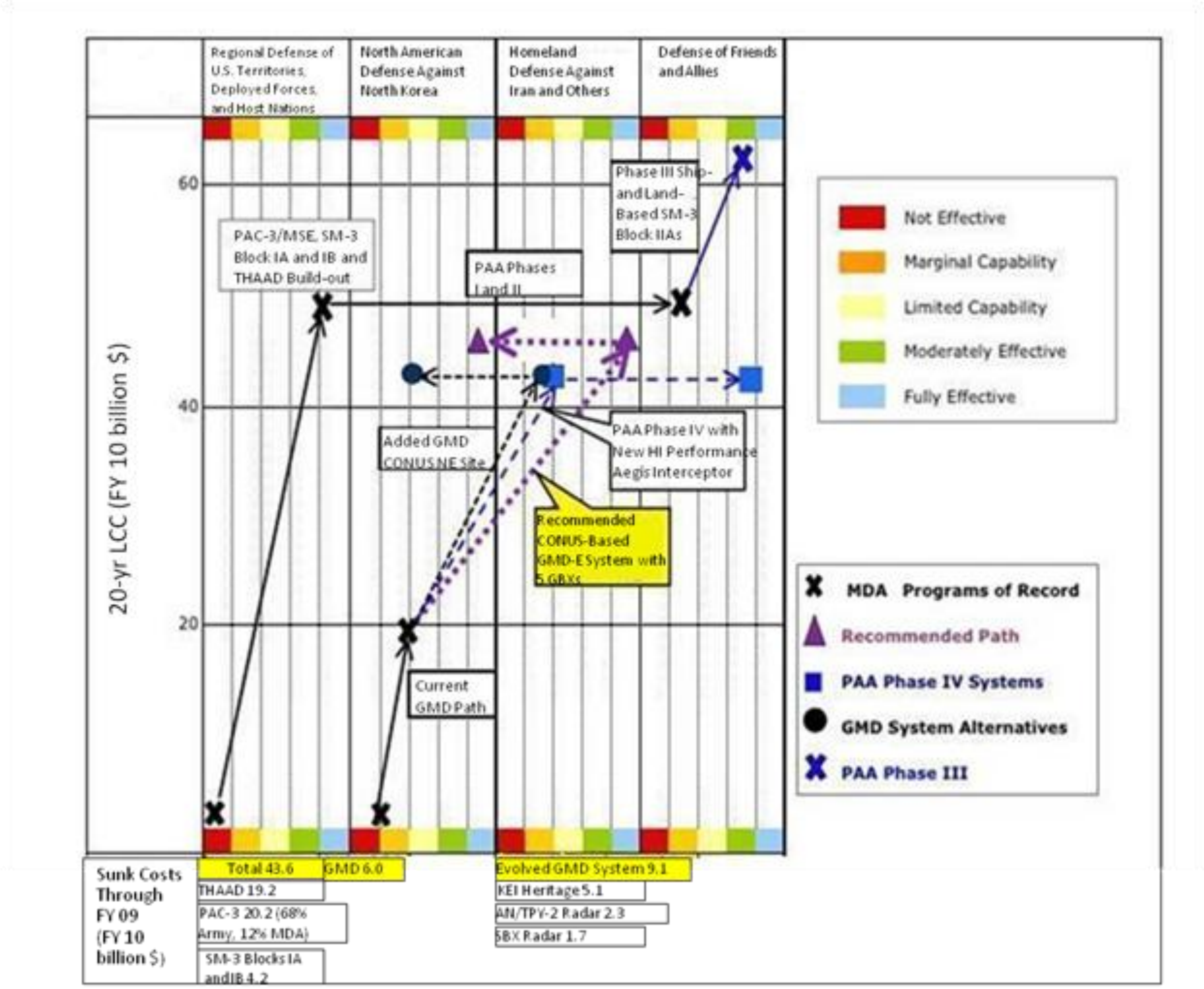

FIGURE 4-6 Effectiveness gain versus LCC. PAA, Phased Adaptive Approach.

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[6] The source data for these defense alternatives are provided in the classified Appendixes I and J.

The current buildout and sustainment path for Aegis SM-3 IA and B, THAAD, and PAC-3 is shown in Figure 4-6 as a solid black line (see the line for the mission "Regional Defense of U.S. Territories, Deployed Forces, and Host Nations"). When THAAD and PAC-3 are completed, they will also inherently provide the initial mission capability for Phases 1 and 2 of PAA (denoted by the black horizontal arrow extending across to the black X in the "Defense of Friends and Allies" mission). Phase 3 of PAA—which adds Aegis ashore, the Block IIA interceptor, a forward-based TPY-2 or FBX radar, and other capabilities—enhances coverage in Europe and adds approximately $12 billion in 20-yr costs (see the solid blue arrow extending to the blue X under the "Defense of Friends and Allies" column). However, Phase 3 of the European PAA is not designed to defend the U.S. homeland.

In the second set of evolutionary pathways for homeland defense, the current buildout and sustainment for GMD to complete and maintain the 30 interceptors at FGA and at VAFB are shown by another solid black line (see black line in the "North American Defense Against North Korea" mission). The effectiveness of this deployment against North Korean threats is limited, and it is not given credit for any significant ability in the mission "Homeland Defense Against Iran and Others" because it is severely limited in defending the eastern United States. At the top of the current GMD buildout path, the dashed black arrow represents an alternative third site for existing GMD interceptors in the northeast United States. This alternative provides single-shot coverage of the eastern United States against threats from the Middle East, with some added benefit against North Korean threats, indicated by the horizontal dashed black arrow toward the "North America Defense Against North Korea" column. Because the current GMD is a single-shot system, it would still be limited in effectiveness. As an alternative with approximately the same life-cycle costs, Phase 4 of PAA is shown as a blue dashed path to the blue squares. This alternative is aimed at providing additional early midcourse flight shot opportunities from Poland against Middle East threats launched at the United States. To be effective in this role, the Poland-based interceptor would have to have a fly-out velocity greater than 5.5 km/sec.

One of the more important points in Figure 4-6 pertains to Phase 4 of PAA: Specifically, it is an expensive solution for improving homeland defense yet limited in effectiveness. The committee's analysis shows that notional interceptors with a fly-out velocity greater than 4.5 km/sec benefit neither European defense nor other Aegis defense missions. Therefore, Phase 4 of PAA, which is the SM-3 Block IIB higher performance interceptor, has value only for an early shot opportunity for homeland defense, provided it has sufficient burnout velocity to preclude being overflown, but comes at a high acquisition and life-cycle cost. An alternative—an evolved GMD system—provides a more effective homeland defense solution and avoids any need for Phase 4 of PAA (see violet dotted arrows for GMD-E).

The message of Figure 4-6 should be clear. Specifically, BMD for forward-deployed forces (i.e., Aegis, PAC-3, THAAD) appears to be on the right track, and the current GMD and PAA Phase 4 for BMD of the United States are headed on two independent paths that are costly and, for U.S. homeland defense purposes, of limited effectiveness. For this reason, the committee recommends an evolved GMD system that provides full shoot-look-shoot (SLS) capability and is substantially more effective than the other potential homeland defense additions to the current GMD buildout. While this path has a 10 percent greater LCC because of the cost of acquiring GBX, it provides robust but still limited defense of the United States and Canada against threats from any source. It is also decoupled from decisions on the NATO defense configuration. Moreover, it finesses the issue of large interceptors close to Russian territory.

A detailed discussion of this evolved path for GMD is provided in Chapter 5. In short, the recommended approach buys more existing supporting sensors and uses them more effectively than would developing any new sensors.

Non-Boost-Phase Systems

The committee's major recommendations with respect to non-boost-phase systems are as follows.

Major Recommendation 2: The Missile Defense Agency should reinstitute an aggressive, balanced midcourse discrimination research and development effort focused on the synergy between X-band radar data and concurrent interceptor observation while closing on the threat. Such an R&D effort should have the following attributes among others:

- Recognition that discrimination is strongly dependent on BMD system architecture, and known synergies should be exploited.
- A continuing program of test and analysis should be implemented to maintain the technical capacity that will be needed to support an adequate level of discrimination as new countermeasures are developed and deployed.
- A serious effort to gather and understand data from past and future flight tests and experiments (including flights of U.S. missiles) from the full range of sensors and to make full use of the extensive data collected from past experiments to generate robust discrimination techniques and algorithms.
- The committee believes that the effort required for success in this endeavor does not need to be overlarge but does require that high-quality expertise be brought to bear. The annual budget outlay, if planned correctly, can be modest compared to current expenditures.

Major Recommendation 3: The Missile Defense Agency should strengthen its systems analysis and engineering capability in order to do a better job of assessing system performance and evaluating new initiatives before significant funding is committed. Cost-benefit analysis should be central to that capability.

- In addition to terminating U.S. boost-phase missile defense systems, MDA should terminate the PTSS unless a more convincing case can be made for its efficacy for the mission that it is supposed to carry out.
- PTSS provides no information that a combination of the SBIRS and the proposed suite of X-band radars with the interceptor sensors will not provide better and at lower cost both initially and over the life cycle. Moreover, as proposed, PTSS contributes little if anything to midcourse discrimination.

Major Recommendation 4: As a means to defend deployed U.S. forces and allies from short-, medium-, and intermediate-range ballistic missile threats, the Missile Defense Agency and the Services should continue investing in non-boost systems such as Aegis, THAAD, and PAC-3, with continued attention to architecture integration of sensors with shooters (sometimes referred to as an integrated battle command system, or IBCS), specifically to implement launch-on-remote (LOR) and engage-on-remote (EOR) firing doctrines.

- EOR is essential for effective coverage of Europe from a small number—say, two or three—of interceptor sites.
- Inputs to the IBCS already include those from Defense Support Program (DSP), SBIRS, and upgraded UHF early warning radars. Maximum use should be made of these data to relieve X-band radars of unnecessary volume or fan search functions, permitting them to concentrate radar resources on tracking and discrimination at the longer ranges permitted when the radars are properly cued to the targets. This

involves little or no new investment. Data latency is a potential problem for the IBCS that should not be ignored.

Major Recommendation 5: As a means to provide adequate coverage for defense of the U.S. homeland against likely developments in North Korea and Iran over the next decade or two at an affordable and efficient 20-yr life-cycle cost, the Missile Defense Agency should implement an evolutionary approach to the Ground-Based Midcourse Defense (GMD) system, as recommended in this report.

- Chapter 5 recommends an evolutionary path from the present GMD system to a system having substantially greater capability and a lower cost than a simple expansion of the present GMD system. The recommended path builds on existing developments and technologies working together to make a more effective system. The concepts are not new and have been well known for at least 40 years. Existing advances in optical and radar technology will enable its realization.
- The evolutionary approach would employ smaller, lower cost, faster burning, two-stage interceptors building on development work by MDA under the KEI program carrying heavier but more capable KVs.
- The evolutionary approach would employ much longer concurrent threat observation by both X-band radars and the interceptor KV's onboard sensor over the entire engagement. The importance of the synergy between these concurrent observations and the shoot-look-shoot (SLS) battle space in maximizing midcourse discrimination effectiveness cannot be overemphasized.
- An additional interceptor site with the new evolved GBI in CONUS together with the recommended radar additions provide SLS coverage of virtually the entire United States and Canada against the sort of threat that can prudently be expected to emerge from North Korea or Iran over the coming decade or so. The recommended evolution would add one additional site in the United States in the northeast, together with additional X-band radars to more effectively protect the eastern United States and Canada, particularly against Iranian ICBM threats should they emerge.
- This improved capability obviates the need for early intercept from bases in Europe, unless they are required for European defense.
- Defense of Hawaii should be provided by Aegis with launch-on-remote capability: THAAD would provide a second intercept opportunity as backup for the Aegis engagement. Hawaii is very small target area for threats from North Korea, Iran, or any other country and can be covered by one Aegis ship located west of the islands. By contrast, modifying the GMD system to provide effective defense of Hawaii against an evolved threat would add substantial complexity and cost.
- Maximize the opportunity for observing the threat complex during most of the threat trajectory until intercept. Addition of stacked TPY-2 radars are recommended for this purpose.
- Make effective use of the high-accuracy data from SBIRS to cue forward X-band radar and concurrent IR sensors on the interceptor kill vehicle, which together contribute most of the discrimination capability.
- The ability to create, communicate, and interpret target object maps (TOMs) among the radar, the battle manager, and the interceptor during the entire engagement—typically hundreds of seconds for a midcourse intercept—increases the probability of successful discrimination. The resulting TOMs with object rankings should be exchanged frequently with the interceptor kill vehicle during its fly-out. This exchange requires taking advantage of the radar's large aperture and power to close

that communication link over longer distances. The TOM's data exchange ability builds on the capabilities demonstrated by programs such as NOE and ERIS and additionally builds on the MDA Integrated Flight Test Plan for GMD, Aegis, and the THAAD interceptor that uses sensor elements with the addition of downlinks from the interceptor to the BMC3 element.

5

Recommended Path Forward

ORGANIZATION

As previously noted, this chapter provides additional details on the recommended evolution for the Ground-Based Midcourse Defense (GMD) system (i.e., the recommended evolution to GMD, called GMD-E in this chapter), as called for by Major Recommendation 5 in the Summary and Chapter 4 of this report, "as a means to provide adequate coverage for defense of the U.S. homeland against likely developments in North Korea and Iran over the next decade or two at an affordable and efficient 20-yr life cycle cost, the Missile Defense Agency should implement an evolutionary approach to the GMD system as recommended in this report."

Before introducing the details of the GMD-E, the basis of Major Recommendation 5 and the key concepts of operations (CONOPS) for providing an effective defense of the United States and Canada at lowest cost are discussed.

BASIS FOR MAJOR RECOMMENDATION 5

As part of its congressional tasking, the committee assessed the practicality of boost-phase defense in comparison to other alternatives, taking into account realistic CONOPS, force structure, effectiveness, life-cycle cost (LCC), and resilience to countermeasures, among other things. In doing so, the committee's analysis led to the following conclusion: The 30 current ground-based interceptors (GBIs), as part of the GMD system deployed at Fort Greely, Alaska (FGA), and Vandenberg Air Force Base, California (VAFB), evolved to their current configuration through a series of decisions and constraints. They provide an early, but fragile, U.S. homeland defense capability in response primarily to a potential North Korean threat. Moreover, the current GBIs are very expensive per round when compared to missiles of similar complexity at the same point in their development and has limited ability to defend the eastern United States against threats from the Middle East.

Consequently, the committee believes that a properly designed midcourse defense is the most versatile and cost-effective way to provide a resilient limited defense of the United States. Specifically, the committee finds as follows:

1. The GMD system lacks fundamental features long known to maximize the effectiveness of a midcourse hit-to-kill defense capability against even limited threats. They could, however, readily be incorporated as part of the recommended GMD-E described in this chapter. The cost effectiveness of various alternatives shown in Chapter 4 suggests that a substantially lower overall cost could be achieved through an evolution that is detailed in this chapter.
2. Discriminating between actual warheads and lightweight countermeasures has been a contentious issue for midcourse defense for more than 40 years (see classified Appendix J for greater detail). Based on the information presented to it by the Missile Defense Agency (MDA), the committee learned very little that would help resolve the discrimination issue in the presence of sophisticated countermeasures. In fact, the committee had to seek out people who had put together the experiments like MSX and High-Altitude Observatory 2 (HALO-2) and who had understood and

analyzed the data gathered. Their funding was terminated several years ago, ostensibly for budget reasons, and their expertise was lost. When the committee asked MDA to provide real signature data from all flight tests, MDA did not appear to know where to find them. MDA showed the committee summaries of results without the data to support them. It appeared to the committee that MDA has given up trying and has terminated most of the optical signature analysis of flight data taken over the last 40 years. In the committee's view, this is a serious mistake.

3. It is clear that advances in technology for both long-wave infrared sensors and X-band radars that can coherently integrate and do Doppler imaging are impressive and offer new opportunities. The fundamental concept for maximizing the effectiveness is presented below (see classified Appendix J for greater detail).
4. In addition to its long-term cost and performance advantages, the recommended GMD evolution as provided in the following sections of this chapter, if adopted, *would decouple the defense of North America from decisions and issues related to the configuration of NATO missile defense, even avoiding altogether the need for PAA.*

In short, the recommended GMD-E involves a smaller, shorter burn interceptor configuration that builds on development work already done by MDA under the Kinetic Energy Intercept (KEI) program, but with a different front end. The heavier, more capable kill vehicle (KV) with a larger onboard sensor provides the capabilities absent in the current GMD system but responsive to the recommended CONOPS, which will be discussed. The GBIs would first be deployed at a new third site in the northeast United States along with five additional X-band radars using doubled Terminal High-Altitude Area Defense (THAAD) Army Navy/transportable radar surveillance (AN/TPY-2) capabilities integrated together at each upgraded early warning radar (UEWR) site and at Grand Forks, North Dakota. At a later time, the more capable interceptor would be retrofitted into the silos at Fort Greely, Alaska, with the existing GBIs diverted to the targets program supporting future operational flight tests.

Much of the basis for the recommended GMD-E has been provided in Chapters 3 and 4. The committee believes that the recommended GMD-E offers a much more resilient although limited U.S. homeland defense against any threat at the lowest 20-yr life cycle cost, and that it can be accomplished within the same requested cumulative 5-yr total obligation authority (TOA) through FY 2016 as in the current plan. Before providing additional information on the recommended GMD-E, it is important to consider the key CONOPS for providing an effective defense of the United States and Canada.

KEY CONOPS FOR EFFECTIVE DEFENSE OF THE UNITED STATES AND CANADA

Defending high-value assets against attack from ballistic missiles requires minimizing the possibility of leakage through the defense for any reason while also minimizing the wasting of interceptors. The contributors to leakage and wastage are discussed in classified Appendix J. In general, these requirements demand, to the maximum extent possible, a level of robustness that can overcome or at least minimize the effects of uncertainties in threat knowledge, the failure of hardware to function as anticipated, or surprises in the adversary's tactics or capabilities.

Realistic Approach to Maximizing Midcourse Discrimination Effectiveness

While good intelligence provides knowledge of the adversary's capabilities, it is rarely perfect, and surprises are to be expected and accommodated. The committee believes that the key to maximizing the ability to discriminate lethal warheads in the presence of countermeasures is exploiting the concurrent intermittent viewing by X-band radar and interceptor optics for an extended (>100 sec) time as the interceptor closes on the target complex. Yet this has been ignored in the current GMD system architecture.

The reason for this seems to be a reluctance to commit an interceptor before having high confidence about the threat complex from some source. Yet, in an attempt to avoid the midcourse discrimination issue, proponents of boost-phase (or early) intercept are willing to commit interceptors before even knowing where the threat is going. Surely, then, we should be willing to commit interceptors after the threat has burned out and its throw weight impact point has been determined by both space-based infrared system (SBIRS) and forward radars so we know where to look for the threat and where the threat is going.

An interceptor launched with only that knowledge, its own observation ability, and enough maneuver ability to cover the remaining uncertainty along with a forward ground-based X-band radar (GBX) observation provides the most valuable threat discrimination tool as the interceptor closes on the threat, hunting for the right target. Has it been wasted? Not unless the adversary expends missiles with no payloads on them. May more interceptors be required? Perhaps, depending on what is observed by the first one, which serves as a scout and together with radar observations provides more data than any other source. But this requires getting time on the side of the defense. It requires maximizing and making efficient use of the battle space, i.e., it calls for shoot-look-shoot (SLS).

Figure 5-1 illustrates how the synergy of concurrent observations can be exploited. The high-resolution X-band radar enables Doppler imaging to measure the dynamic behavior of each object in the threat and to see unique signatures from scattering centers as the objects spin, tumble, and nutate in response to disturbances due to deployment methods. It also provides accurate metrics on the position and state vector of each object in the complex and provides all that information through the battle manager to the interceptor to correlate with its optical measurements. The interceptor optics also measure the time-varying thermal signature, which provides information about thermal mass, object dynamics, and the movement of objects in the threat; this information is transmitted back to the battle management command, control, and communications (BMC3) for continued use. Together, these observations make countermeasures more difficult over the total viewing and engagement time. Moreover, countermeasures that may be effective against the first interceptor will in many cases have outlived their effectiveness against subsequent interceptors.

Exoatmospheric discrimination by definition requires identifying the threatening reentry vehicle (RV) from among the cluster of other nonthreatening objects that will be visible to the defense's sensors after the end of powered flight. Initially the nonthreatening objects may be "unintentional"—for example, spent upper stages, deployment or attitude-control modules, separation debris, debris from unburned fuel, insulation, and other components from the booster. However, as threat sophistication increases, the defense is likely to have to deal with purposeful countermeasures—decoys and other penetration aids and tactics to include salvo launches and antisimulation devices—that adversaries will have deliberately designed to frustrate U.S. defenses.

Evaluating discrimination effectiveness is an uncertain business. One should avoid overstating the ease with which countermeasures that are theoretically possible can actually be made to work in practice, especially against advanced discrimination techniques using multiple phenomenologies from multiple sensors and exploiting the long observation time that midcourse intercept makes possible. It is perhaps noteworthy that U.S. (and U.K.) experience with the development of high-confidence penetration aids during the Cold War was of mixed success. It would be difficult for an adversary to have confidence in countermeasures without extensive testing, which the United States might be able to observe and gather data on that would permit defeating the countermeasures.

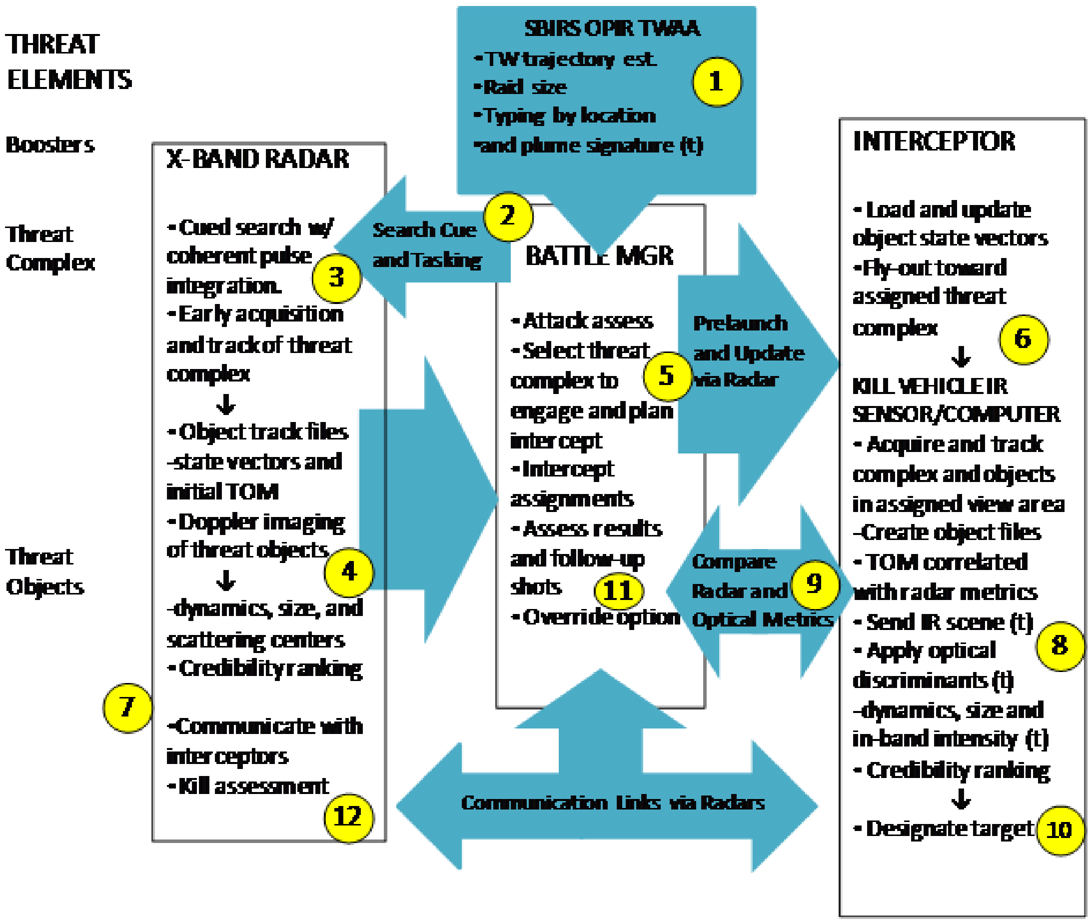

FIGURE 5-1 Synergy of concurrent radar and KV optical observations. OPIR, other program infrared; TWAA, tactical warning and attack assessment; IR, infrared.

The art of midcourse discrimination, developed over many decades, does not provide perfect selection of RVs, but the committee believes that by designing a ballistic missile defense (BMD) architecture based on the capabilities described below, an adequate level of discrimination performance can be achieved in the near term, and that this approach has a reasonable chance of keeping the United States generally ahead in the contest between countermeasures and counter-countermeasures. This having been said, the reader should understand that there is no static answer to the question of whether a missile defense can work against countermeasures. It depends on the resources expended by the offense and the defense and the knowledge each has of the other’s systems.

While the current GMD may be effective against the near-term threat from North Korea, the committee disagrees with the statement in the BMDR concluding that this capability can be maintained “for the foreseeable future.”[1] The committee understands this to mean the next decade or so. If the threat is to be countered for the foreseeable future, the United States needs to take the steps outlined below to maintain discrimination capability.

The BMD system capabilities that provide reasonable discrimination prospects are mostly supported by the available hardware and techniques, but they have yet to be included in the existing or planned GMD architecture. The system capabilities include the following:

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[1] Department of Defense. 2010. *Ballistic Missile Defense Review Report*, Washington, D.C., February, pp. 9, 15, and 47.

1. The threat complex must be observed at frequent intervals by instruments capable of obtaining discrimination data from the time of booster burnout until intercept occurs (see Figure 5-1).
2. Observation of the threat is possible and necessary in both microwave and optical bands, and the resulting data must be fused into a target object map (TOM) to be used by the interceptors.
3. While other observations can be useful, it is the high-resolution data from X-band radar and IR seekers such as those on the kill vehicle (KV) that contribute most of the discrimination capability. Those instruments must be located, tasked, and equipped to provide these data as soon as practical after booster burnout onward, with minimal distractions for housekeeping and other duties. Investment in low-resolution measurements should have lower priority than investments in high-resolution measurements.
4. The ability to form and interpret TOMs over a time that is typically many hundreds of seconds for midcourse intercept increases the likelihood of successful discrimination. The TOMs must therefore be exchanged frequently with the interceptor KVs during fly-out.
5. Data from the KV’s onboard seeker can be used to improve the discrimination effectiveness of subsequent intercept attempts and should therefore be downlinked from the interceptor during flight.
6. To take full advantage of combined radar and KV observations, the BMD system architectures and firing doctrine should enforce and exploit the maximum battle space for SLS capabilities.

More generally, the committee believes that a long-term approach to midcourse countermeasures involves the following:

1. Recognizing that discrimination is not separate from the overall BMD system architecture and that synergies should be exploited where possible, specifically through layered defenses such as postboost intercept and shoot-look-shoot (SLS) tactics.
2. Understanding that the countermeasure threat is not constant and that there is no permanent solution. A continuing program of test and analysis is necessary to maintain the technical capacity that will support an adequate level of discrimination as new countermeasures are developed and deployed.
3. Implementing a more realistic and robust program to gather data from flight tests and experiments (including on flights of U.S. missiles) from the full range of sensors and making full use of the extensive data collected from past experiments to continue developing the applied science from which robust discrimination techniques and algorithms can be developed.
4. Maintaining an active R&D program on discrimination techniques.

Radar Discrimination

Opponents of BMD systems correctly point out that the system is defective if it lacks the ability to select threatening targets amongst the many objects that accompany them. This ability can be enhanced by observation over the longest possible time by X-band radars. Classified Appendix J discusses issues of radar discrimination, with the conclusion that an adequate solution of the problem is possible. A generalized summary of those considerations is as follows.

- *Bandwidth*. X-band radars are used in defense systems to perform precision tracking and target classification functions. The choice of this band by both U.S. and foreign radar engineers is based partly on the broad system bandwidth inherent in X-band operation, which allows transmission of wideband waveforms that resolve and measure individual objects without interference from others in a target cluster. Wideband waveforms permit direct measurement of the radial extent of each object (called range profiling, a standard approach to radar target classification in air and missile warfare). The radial extent of objects that change their aspect angle by a significant amount over the observation time—for example, rotating objects or stable objects viewed from a position outside the plane of the trajectory—provides measurement in two dimensions.
- *Cross section*. For objects that are resolvable with wideband waveforms, tracking radars can collect and measure the radar cross section (RCS) of each object within the target cluster. The absolute RCS is sensitive to details of the object's size, shape, surface roughness, and material.
- *Range Doppler Imaging*. Wide-bandwidth echoes from an object, collected over an extended train of coherent pulses, can be processed to provide a two-dimensional image of the object, as illustrated in Figure 5-2.[2] Such images can be collected simultaneously on objects in a target cluster while they remain within the beamwidth of the radar. Some fraction of the objects can be expected to rotate at rates that permit rapid classification of small or irregular nonthreatening debris. Decoys too small to present a threat can also be discriminated over periods of several seconds. The coherent process used in imaging also improves the sensitivity of a radar so that objects with cross sections smaller than required for acquisition of the track can be located and their relative positions measured.
- *Position measurement*. With adequate signal-to-noise ratio, a monopulse tracking radar can limit measurement error to less than 1 percent of its beamwidth. Over extended track periods, the relative positions can be refined by a further order of magnitude. Along with measurement of relative range to within fractions of a meter, using wideband waveforms, these position data provide a three-dimensional target object map that can be converted to the angular coordinates of a homing seeker, ensuring proper registration of each object in the target cluster.
- *Precession and nutation*. The range-Doppler image of each object is sensitive to small angular motions of the object, representing precession and nutation of its axes.[3] Observation of these parameters over an extended period provides additional discriminants that are not available by other means.
- *Object mass*. Objects having insufficient mass to constitute threats can be excluded as targets for defensive action. To the extent that forward-based X-band radar siting permits viewing the threat before booster burnout, tracking of the booster through burnout and deployment of the RV can be useful in this regard.

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[2] Joseph M. Usoff, MIT Lincoln Laboratory. 2007. "Haystack Ultra-wideband Satellite Imaging Radar (HUSIR)," *2007 IEEE Radar Conf.*, Boston, Mass.,April 17-20, Plenary Session, pp. 17-22, ©IEEE.

[3] V.V. Chen and H. Ling, Naval Research Laboratory. 2002. *Time-Frequency Transforms for Radar Imaging and Signal Analysis*, Artech House, Norwood, Mass.

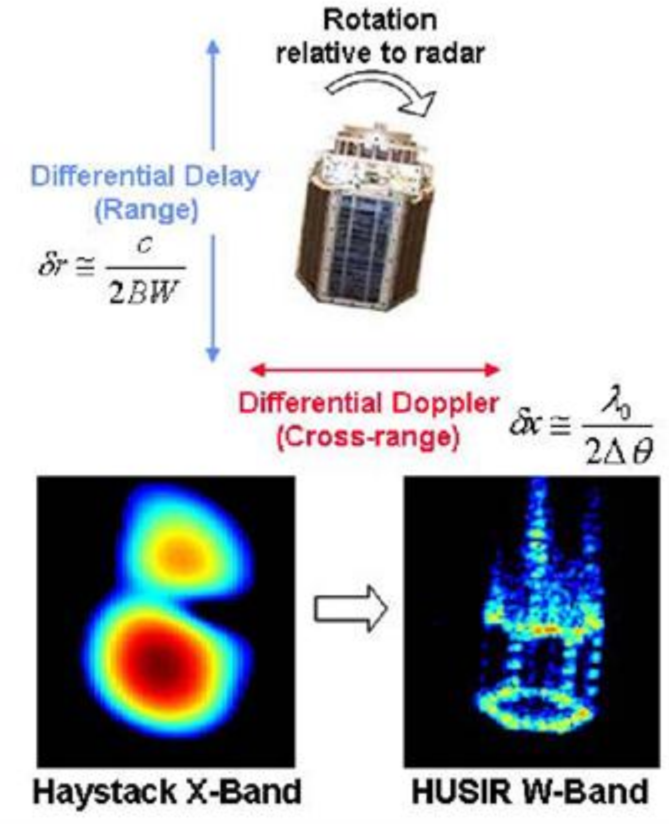

FIGURE 5-2 Example of ISAR satellite imaging from the Haystack radar complex.

- *Capabilities of other radars*. It has been suggested that the Aegis AN/SPY-1 and the upgraded UHF early warning radars can provide discrimination, or at least classification, of target objects. These radars have only limited range resolution capability, far below that of the X-band radars.

The signal bandwidth of the UHF radars is limited to a few megahertz, both by equipment design and by ionospheric propagation effects. The resulting range resolution is measured in tens of meters. The beamwidths of the UHF radars are approximately 2 degrees. The lack of resolution increases the probability that two or more objects will lie in the same resolution cell, precluding accurate measurements of any sort on the individual objects that would be useful for discrimination or classification. Widely spaced targets might permit classification, but the contribution to discrimination and target selection is negligible.

In summary, it is concluded that observation over the longest possible time by X-band radars is a prerequisite for midcourse discrimination. These radars were designed to perform this function, and it is essential that they be assigned to perform tracking and discrimination functions using all their resources, leaving search and warning to the low-resolution radar systems and overhead sensors that were designed for that purpose. The failure to exploit fully the ability to extend the synergy between the two sensor classes, which permits extending the range of the X-band radar tracking and discrimination, has unnecessarily compromised the performance of the present BMD system.

Finally, although much of the early work on decoy discrimination involved optical techniques, it appears that with the advent of very capable X-band radars, MDA has shifted away from this approach over the past decade. While the committee largely agrees with this shift in emphasis, work on sensors and optical discrimination should be continued because optical techniques have not been exploited to their fullest as the committee recommends. Classified Appendix J provides additional discussion and analysis related to classical optical discrimination.

Fundamental Precepts of a Cost-Effective Ballistic Missile Defense

The following principles should be respected:

1. Understand the threat variables and the adversary's objectives and design to deny them;
2. Provide margin and options for unanticipated events or behavior;
3. Make time an ally not an enemy;
4. Keep it as simple as possible;
5. Delegate responsibility for real-time decisions to the proper level rather than centralize them; and
6. Make the best use of the nature of the assets available and minimize the need for new ones.

The committee finds the current GMD system deficient with respect to all of these principles.

Functional Delegation

Table 5-1 displays the functions that must be performed in defending against a ballistic missile attack independent of where it is launched from or where it is going. It indicates what sensors are needed and what they do and do not provide in the way of information that the defense can use. In effect, the information in the table helps define the CONOPS and the architecture. The following discussion amplifies Table 5-1 vis-à-vis the four missile defense missions discussed throughout this report.

Threat Characterization

The characteristics of threats in the scenarios delineated by the congressional task are discussed generally in Chapter 1 and in detail in classified Appendix F. In addition, Chapter 2 presented the challenges of the timelines for boost-phase defense. Here, some timelines are recapped as the committee considers CONOPS for the various missions.

- An intercontinental ballistic missile (ICBM) launched from central Iran to the U.S. East Coast would have a maximum range total flight time of about 40 minutes. If it were liquid propelled, the boosted portion of that flight time would last about 250 sec, and if solid propelled, it would last about 180 sec. Similar flight durations would apply to threats from North Korea. At least some if not all solid-propelled missiles and all liquid-propelled missiles would have thrust termination capability and could also use excess energy to loft or depress their trajectory at less than maximum range.
- A three-stage, 5,600-km range solid-propelled intermediate-range ballistic missile (IRBM) capable of targeting London and virtually all of Eurasia from central Iran would have a maximum range flight time of about 24 min and a boost time about 180 sec. A liquid IRBM with similar capability would have a boost burn time of about 200 sec. Either of these could be lofted or depressed at the expense of range.
- In the Middle East or northeast Asia, the defense of allies and/or U.S. forces would face shorter range threats, with total flight times of 15 min or less and typical maximum range apogees of 600 km or less. Boost times would probably be no more than 120 sec with burnout altitudes often less than 100 km. These timelines would

TABLE 5-1 Recommended Missile Defense CONOPS and Function Delegation

Phase of Threat	Function	Command Level	Intelligence	Surveillance Sensors	Combatant Commander	Battle Manager	Fire Unit	Tracking and Discrimination
Peacetime	Surveillance	Approve doctrine and ROE for lower levels	Monitor developments and assess capabilities, order of battle, and intentions	Broad area surveillance	Establish ROE for operations on basis of NCA guidance	Maintain defense connectivity and validate readiness	Maintain readiness	
Heightened tensions	Alert	Increase DEFCON level	Estimate intentions and tactics of adversary	Respond to Defcon status with focus on adversary AOR	Task surveillance, assets, alert AOR defense focus and set contingent ROE	Active and maintain readiness and status of defense resources	Check and verify readiness status	Prepare to or go active in designated surveillance sector
Threat launch and powered flight	TWAA	Delegate defense authority to appropriate COCOM	Determine adversary's remaining assets, their locations and capabilities	Determine raid size, throw weight, impact prediction, missile typing. Cue defense acquisition and tracking sensors	Determine priority of assets to be defended against this attack based on ROEs	Select defense resources and plan engagements	Select assets and maintain readiness to fire	Concentrate resources on search and detection
Threat midcourse flight	Defense acquisition, tracking and engagement planning	Monitor	Support NCA/COCOM response and contingency planning	Maintain surveillance for follow- on attacks from same or other sources	Authorize battle manager to commit	Select firing doctrine; authorize fire unit(s) to engage when forward-based radars verify threat	Prepare interceptor(s)	Cued or self-cued search, track and characterization of threat objects
	Engage and plan 2nd shot	Monitor	↓	↓			After forward defense radar acquires threat, commit interceptor(s)	Establish track files and state vectors for all objects
	Target designation	Implement contingency plan	↓	↓			Prepare backup interceptors Commit additional interceptors(s) as required for other credible objects	Rank objects and transmit handover of TOM to interceptor Update TOM periodically to interceptor, receive sensor data downlink and observe intercept
	Post-designation assessment	Response plan	↓	↓	Damage assessment and response	Look at both interceptor and radar TOMs and radar designated target objects and object ranking to determine need for additional intercepts	Commit 2nd shot for any failure	Maintain track on all objects
	Intercept	Monitor				Kill assessment and decision for 2nd shot		
Reentry	Follow-on engagements Terminal engagement within atmosphere	Monitor						

NOTE: AOR, area of responsibility; ROE, rules of engagement.

also apply to launches from tramp steamers or submarines about 1,000 km off the coast of the United States or allied homelands. Accordingly, those threats could not be engaged in boost phase from space but might be engaged in the atmosphere during boost by forward-based platforms—either airborne or sea-based—if they were close enough.

- Based on public descriptions of the testing carried out by a potential adversary, it is likely that any threat missile launched would be part of a salvo of near-simultaneous launches of similar missiles or a variety of missile types. The salvo might be launched from sites a few kilometers apart and/or widely separated. Missiles of different types in a salvo might have different missions such as rolling back forward-based radars and forces as well as strategic targets. Similar missiles in a salvo might also have different but complementary roles such as an electromagnetic pulse precursor or defense suppression.
- Precursor attacks in particular must be considered a possible element of any threat raid because they can be implemented by any missile after exit from the atmosphere.

Countermeasures

At some point, countermeasures of various kinds should be expected. While these may or may not be observed in tests, a reasonable assumption would be that they will be similar to those tested elsewhere.

Operational Testing in Realistic Engagements Is Costly but Necessary

Confidence in U.S. defense components and their ability to function as expected under stressing conditions can only be established by end-to-end operational tests that are realistic albeit limited in scope and number and by continued use of unmodified deployed systems during the life of the deployment. Of necessity, any one of these tests is expected to be constrained by cost to one-on-one or few-on few-engagements, but it would certainly possible to inject realistically simulated data into the surveillance, acquisition, and tracking sensor measurements and messages to stress the system's ability to function properly while handling larger raids. In addition, to serve as a training tool for the operators and to build their knowledge and confidence, the battle simulation facility could use real system elements in the loop and introduce failures or unexpected threat behavior.

Defining, developing, manufacturing, and deploying multiple systems to defend against various often ill-defined potential offensive systems is a significant challenge. In response to this challenge, MDA, in concert with the DOD Operational Test Assessment Office and the Services test organizations, has created an overarching Master Integrated Test Plan. A key concern is the signatures of incoming missiles, reentry vehicles, and associated penetration aids, which cannot precisely be duplicated or tested. The availability of test missiles also limits the number of flight tests that could be conducted with the GBIs at FGA and VAFB.

The committee believes that the MDA Master Integrated Test Plan developed and approved by the Office of Testing and Assessment (OTA), is a reasonable approach to developing estimates of the initial reliability of the deployed systems while considering the complexity and costs of any potential test plan. This master plan also takes advantage of significant simulation testing of all the MDA systems. However, the committee has not seen a follow-on operational test plan for deployed systems that would provide an ongoing reliability assessment with associated confidence levels. In short, today's deployed GBIs do not have identical configurations, and the missile could have different reliabilities and confidence levels that would need to be utilized by the war planners. MDA does maintain an accurate configuration for each deployed GBI, so that the situation of "no two alike" does not now appear to be an important concern. In summary, MDA's comprehensive, overarching Master Integrated Test Plan for all of its deployed assets and supporting activities was distributed in July 2010, but the actual results and benefits of the plan remain to be seen.

Testing aside, the most important contributor to an effective missile defense is the robustness of the architecture and the CONOPS that define its capabilities, even given uncertainties in the threat and reliability of the system elements. For that reason, the committee believes it is important to specify the CONOPS and the architecture.

Conclusions on CONOPS for Defense of the United States and Canada

The committee draws some conclusions and guidance on CONOPS for defense of the United States and Canada from Table 5-1 and the analysis in Chapter 2.

1. There is no tenable place from which to launch surface-based or air-launched interceptors within 1,000 km of central Iran, where that country's longer-range missiles are likely to be based for security reasons. Therefore, it would not be practical to engage any long- or medium-range threats during their boost phase and they would have to be engaged during their midcourse or terminal trajectories. Shorter range threats have burn times too short and burnout altitudes too low to engage before their midcourse or terminal phase of flight.
2. In the view of this committee and based on 50 years of knowledge and experience with ballistic missiles and defense against them, midcourse defense with a terminal underlay where needed would be the most cost-effective defense against ballistic missiles. Among its other benefits, midcourse has time on its side, and this time should be used wisely.
3. When carefully examined, early intercept is not early enough to avoid the issues of midcourse discrimination, and it reduces the time available for viewing, which is so important for midcourse discrimination. Moreover, the schemes recommended to circumvent that problem are vulnerable to the deployment scheme chosen by the attacker. However, early intercepts do sometimes offer additional shot opportunities and might also constrain an adversary's payload deployment time, making effective countermeasures potentially more difficult.
4. It should therefore be recognized that no practical defense scheme can avoid the need for midcourse discrimination. Until that reality is acknowledged, there will be no end to poorly thought out schemes proposing to avoid the need for midcourse discrimination.
5. Whether decoys can be readily discriminated, particularly in the face of antisimulation techniques, remains a contentious subject however. The combination of observations for more than 100 sec by an interceptor-mounted optical sensor that is closing on the threat complex, together with concurrent X-band radar observations and a firing doctrine that exploits the battle space available for SLS engagements, offers the greatest probability of being able to separate real threatening objects from decoys and other objects and should be central to any defense of the U.S. homeland, allies and friends, and U.S. deployed forces.
6. To effectively exploit these capabilities, interceptors must be within sight of a radar—not necessarily the same one—in order for the radar to communicate with the interceptor at any time from shortly after launch until intercept. This means that while tracking the interceptor and target, the radar(s) must be able to transmit in-flight updates based on radar or battle manager observations and to receive and relay downlinks from the interceptor once its sensor is uncapped and it sees and decides to engage. The interceptor then must have the ability to receive communication uplinks

at any time after its first stage burns out (except during staging events) and to send down to the battle manager, via the radar data on its observation of the threat any time after sensor uncap, its decisions about ranking and which object it selects to intercept.

7. The observed and processed data transmitted from a midcourse interceptor should include processed focal plane data as well as all object track files and their ranking for use by the battle manager for second-shot decisions. It is expected that the focal plane will be read out at a rate of at least 50 Hz and that the final image messages should be at a rate of at least 3 Hz within 0.5 sec of intercept. While it is recognized that this may dictate high bit rates in the last report burst of data, earlier reports can be at rates no higher than once every 3 to 5 sec until the last 5 to 10 sec before intercept. This is particularly important for the detection of some countermeasures.
8. Complementing the interceptor capabilities indicated here is a need for enough X-band radars with sufficient acquisition range and capability to observe, image, and measure the dynamics of threat objects over as much of their trajectory as practical to support both discrimination of warheads from other objects and firing solutions and two-way communication for interceptors even in the presence of countermeasures and to perform kill assessment for SLS.
9. AN/TPY-2 X-band radars forward-based in Japan and in eastern Turkey or Azerbaijan, for example, offer a very important capability, particularly for the defense of allies and deployed U.S. forces, but also for the defense of the United States. Cued by the Defense Support Program (DSP) or the SBIRS, they provide the earliest precision tracks that can be propagated forward in time and used for committing interceptors thousands of kilometers away. They should be appropriately defended against a rollback attack by short-range, short-time-of-flight ballistic or cruise missiles as well as against infiltrating ground attack.
10. With capable forward-based radars, it is possible for shorter range engagements, where time is not an ally, to commit interceptors shortly after threat burnout. Remaining uncertainties during the interceptor's boost can be removed by modest divert maneuvers sacrificing little fly-out velocity.

RECOMMENDED GMD EVOLUTION—THE INTERCEPTOR

Overview

As previously noted, the committee's analysis shows, among other things, that the GMD system does not take advantage of fundamental features long known to maximize effectiveness in a midcourse hit-to-kill defense capability against threats to the U.S. homeland. These features can still be incorporated at a lower overall cost through the recommended GMD-E described here.

In short, the recommended evolutionary GMD-E would provide much longer and more effective concurrent threat observation during engagements by both X-band radars and the onboard sensors of the KV while closing on the threat complex. This combination, coupled with SLS battle space and firing doctrine supported by robust two-way communication, is a powerful tool for discriminating real warheads from countermeasures and for reducing leakage. Precluded in the current GMD architecture, this combination would also provide a more effective U.S. homeland defense capability, albeit still a limited one by virtue of the number of interceptors deployed. Moreover, it would minimize or eliminate the need and cost for so-called early midcourse engagements from Europe-based large interceptors (greater than 4.5 km/sec fly-out velocity).

The recommended GMD-E—a CONUS-based system—takes advantage of work already done by MDA, along with previously demonstrated technology and implementations long known to be effective but unfortunately not considered in the current FGA deployment.

Instead of building more of the current interceptors or in-flight interceptor communication stations (IFICSs), the evolution would employ a smaller, two-stage interceptor based on rocket motors developed by the KEI program before it was terminated. It is referred to in this report as the GMD-E interceptor.

As described in Chapter 2, the KEI program was initiated several years ago to try (unsuccessfully) to achieve boost-phase intercept with a high-acceleration, high-velocity, two-stage 60-sec-burn booster (35-sec-burn first stage, 25-sec-burn second stage), plus a two-pulse third stage, plus a light KV. Careful analysis at the time would have shown that goal to be impractical for any operationally realistic deployment location, but the booster configuration had been developed through successful ground firings of each stage when the program was terminated in 2009.

Ironically, the first-stage rocket motor of the KEI, together with a similar, but less demanding second stage would be an ideal candidate for the recommended GMD-E interceptor. Using such technology, one can construct a notional interceptor with a total boosted burn time of approximately 70 sec. With the elimination of the KEI third stage (note: the first and second stages now no longer have to propel the mass of the third stage), the recommended GMD-E interceptor could carry a heavier, more capable KV to greater burnout velocity. Such an interceptor would be very well suited to the midcourse mission of the recommended GMD-E. It offers large footprints, and with the features recommended, provides ample battle space to defend the United States and Canada; it also has resilience to threat uncertainties and a margin for the growth of payload mass. This notional GMD-E interceptor would have a burnout velocity of approximately 6 km/sec,

Using the recommended GMD-E interceptor, a third CONUS site would be added in the northeastern United States, e.g., at Fort Drum, New York, or in northern Maine, to protect the eastern United States and Canada against any potential threats that are limited in nature. These changes, along with a recommended new variant of existing X-band radars (discussed below), provide the important battle space for SLS capability for homeland defense. These changes also provide the best opportunity for discrimination against offensive countermeasures utilizing the combination of properly located X-band radar capabilities and optical sensors on the interceptors themselves as they close on the threat complex.

The recommended GMD-E interceptor is compared to the current GBI and a Standard Missile (SM)-3 Blocks IIA and IA in Figure 5-3 (see classified Appendix J for greater detail). Note that the recommended GMD-E external size is identical to that of the KEI.

An additional perspective on the projected capabilities of the recommended GMD-E may be found from Figure 5-4, which shows the fly-out fan for the recommended GMD-E interceptor easily reaching out to engage beyond 4,000 km in range down to 100 km altitude for the leading edge of defended area. The limiting factor on the fly-out envelope is the KV battery, which is sized for 1,100 sec of operation. As noted to the right of the figure, there is ample payload margin for an even heavier KV if more divert capability is desired.

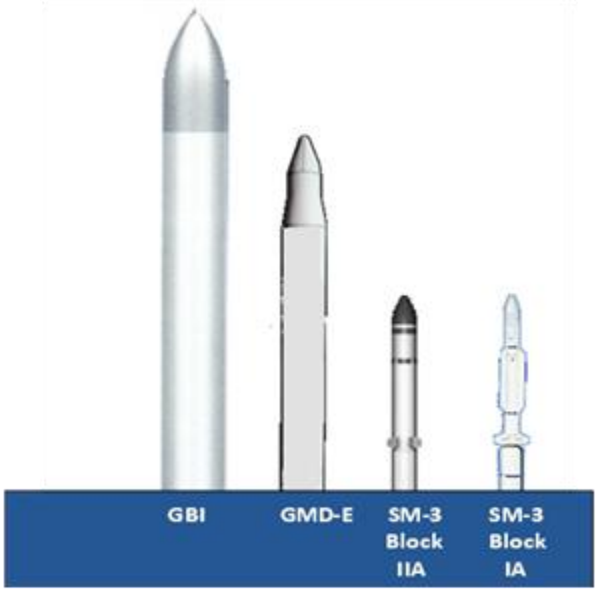

FIGURE 5-3 Comparison of current systems. SOURCE: Extracted from Craig van Schilfgaarde, David Theisen, Steve Rowland, and Guy Reynard, Northrop Grumman Corporation, “An Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives: Northrop Grumman Perspective,” presentation to the committee, July 13, 2010. Courtesy of Northrop Grumman Corporation.

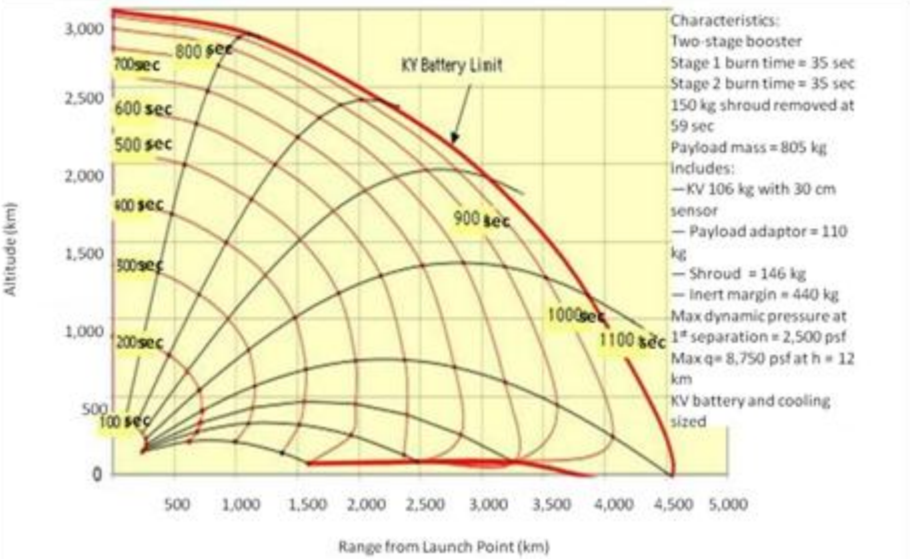

FIGURE 5-4 Recommended notional GMD-E interceptor fly-out contours with 6 km/sec interceptor fly-out contours and two-stage 70-sec total burn.

GMD-E Midcourse Kill Vehicle

As set forth above, the KV for the GMD-E interceptor is more capable and heavier than the exoatmospheric kill vehicle (EKV) and therefore supports the resilient CONOPS underpinning a multiple-SLS firing doctrine. It has all the recommended features described in Chapter 3, including an X- and S-band communication transponder of sufficient transmit power and antenna configuration for two-way link closure with either X- or S-band radars, radiation-hardened electronics, and battery capacity for 1,100 sec.

The KV’s long-wavelength infrared (LWIR) sensor can see threat objects at room temperature at a range of 2,000 km and small, colder objects shortly thereafter as range-to-go decreases. This longer acquisition range and acuity is achieved with a 30-cm-diameter aperture and a 256 × 256 two-IR-band focal plane array. A visible band array is also recommended. The focal plane and adjacent optics are cooled down to about 100 K in flight before sensor uncap using a gas blow-down system. This provides as much as 200 sec of observation by the onboard sensor in most first-shot engagements, thus maximizing opportunity for concurrent viewing of the spatial and temporal dynamics of target objects by both the onboard optical sensor and radars in view while the interceptor is closing on the target complex. The analysis used to size the sensor is provided in classified Appendix J.

The KV Divert and Attitude Control System (DACS) is sized for a divert capability of 600 m/sec, which, with the almost-1-degree sensor field of view, can handle handover uncertainties of ±30 km or more. The large payload margin of the interceptor would allow additional divert and step staring by the sensor, which in turn would permit even larger handover uncertainties if desired.

The KV has an encrypted, dual-channel communications transponder with both X- and S-band two-way encrypted links compatible with either type of radar as the ground transmitter and receiver. This provides two-way communication with interceptors after end-of-first-stage-burnout for radar TOM updates or override commands from the battle manager. The encrypted downlink has enough bandwidth to display what the onboard sensor sees and designates from sensor uncap to intercept.

A notional inboard profile of the recommended GMD-E KV is shown in Figure 5-5, and a weight statement is shown in Table 5-2.

Figure 5-6 displays the sensor and KV fully fueled (“wet”) mass as a function of cooled sensor aperture, given the performance and characteristics shown in Table 5-2. Note that the GMD-E kill vehicle fits nicely on that curve, albeit with less functionality included. A feature known as a “kill enhancement device” is incorporated into the recommended KV. The basic concept is to increase the cross section of the KV around the seeker with a lightweight array to handle very closely spaced objects. The Exoatmospheric Re-entry Interceptor Subsystem (ERIS) KV flown in 1991 had such an array. It employed a lightweight, inflatable tubular frame, which supported a thin membrane that was deployed several seconds before intercept on the basis of estimated time-to-go. While ERIS achieved direct body-to-body impact and also demonstrated the ability to select the aim point, the kill enhancement device provided a hedge against some countermeasures. The ERIS KKV, with its lethality enhancement device deployed, is shown in Figure 5-7.

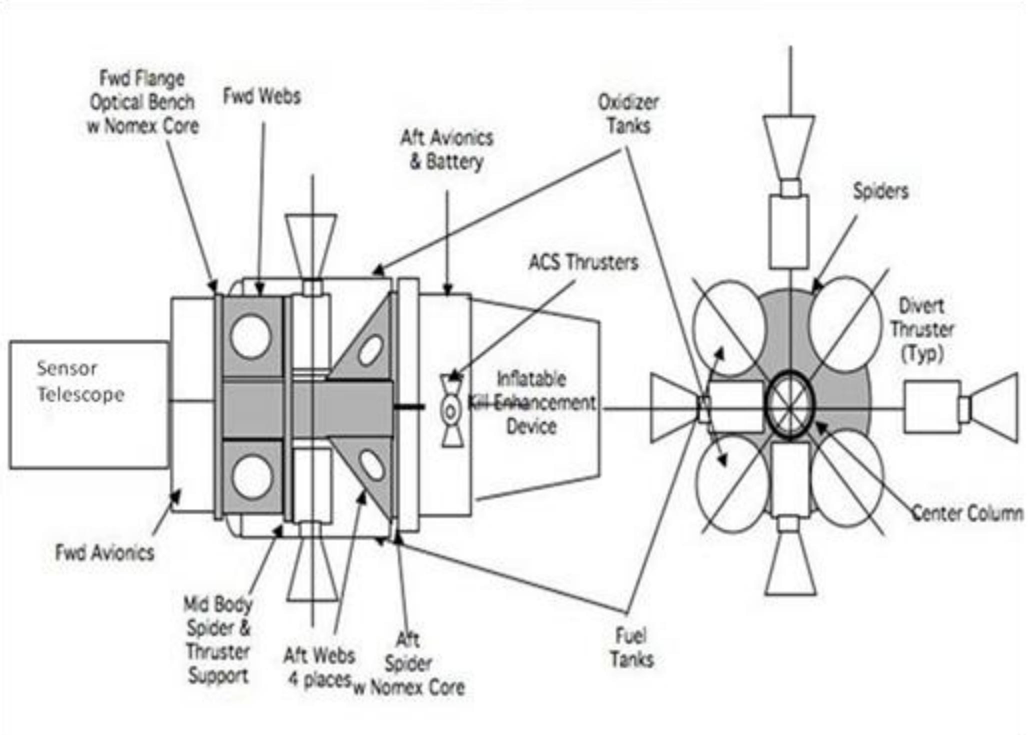

FIGURE 5-5 KKV notional configuration. Gray denotes Kevlar/epoxy frame. SOURCE: David K. Barton, Roger Falcone, Daniel Kleppner, Frederick K. Lamb, Ming K. Lau, Harvey L. Lynch, David Moncton, et al. 2004. *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues*, American Physical Society, College Park, Md., October 5, p. S250.

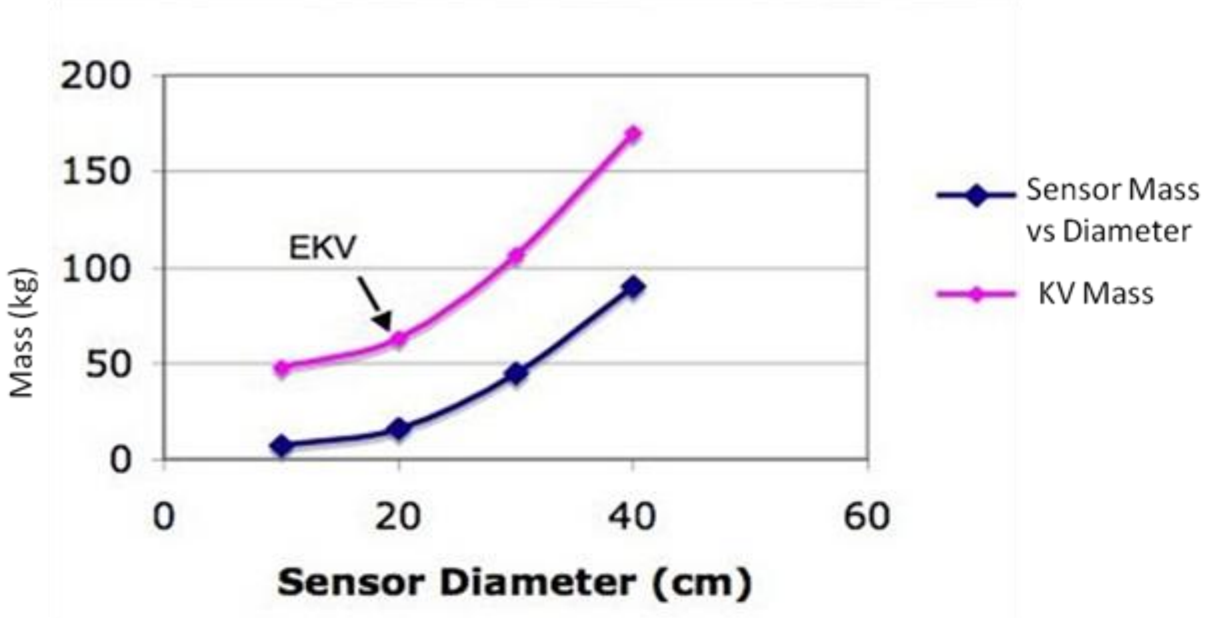

FIGURE 5-6 GMD-E midcourse KV and sensor mass as a function of aperture diameter.

TABLE 5-2 Recommended notional GMD-E KV Mass Properties Statement

Liquid Midcourse KV with 30 cm 45-kg Sensor Segment orSubassembly	Mass (kg)	Notes
DACS		Adjusted for 4 *g*
Pressure regulator	0.50	Assumes 4 divert thrusters
Divert thrusters	4.60	ACS required assumed = 0.1 × divert
ACS thrusters	0.46	Closing velocity = 8-10 km/sec
Value drivers	Included	Maximum total time of KV operational = 1,100 sec
Manifold	Included	
		Sized for *4* g in last 10 sec
Seeker less IMU including cooling	45.00	
Contingency for FPA shielding	1.00	
IMU	1.00	
Avionics[a]		
Separation system	0.50	
Ordnance initiate lines	0.25	
Kill enhancement device	5.00	Rough estimate
KV primary battery	5.00	Estimate based on other programs
KV basic structure and install	8.00	Tanks used as load-carrying structure but Kevlar Epoxy composite structure for high axial and lateral acceleration
Total KV dry weight less tank	81.31	Total ΔV in m/sec + 10% ACS
Useful fuel and oxidizer	19.30	Added ACS fuel at 10% of divert
ACS and press fraction of useful, 10%		
ACS and pressurization fuel, 10%	1.93	Propellant trapped in system 20% of fuel load
Unusable propellant fraction, 3%		
Unusable propellant	0.58	Conventiional pressure tanks
Tankage	3.98	Account for ACS/pressure fuel used but not effective for thrust
Subtotal of KV wet	106.52	
I_{sp} of propellant (sec)	300	
I_{sp} (effective) after ACS and pressurization fuel	285	
ΔV from rocket equation	602	
ΔV desired in m/sec (input)	600	
KV mass with 15% fuel remaining	88.47	
Thrust for 4 *g* at 15% fuel load	3,468	Based on 4 *g*
g at full fuel load	3.32	

NOTE: ACS, altitude control system; IMU, inertial measurement unit; FPA, focal plan array; FTS, flight termination system; TM, telemetry.

[a] Avionics includes guidance/control computer, tactical communications transponder, KV electronic safe arm, FTS antenna (nontactical), FTS battery, command destruction recovery signal, X-band antennas, X-band TM, power divider/hybrid coupler, J Box, control module, logic.

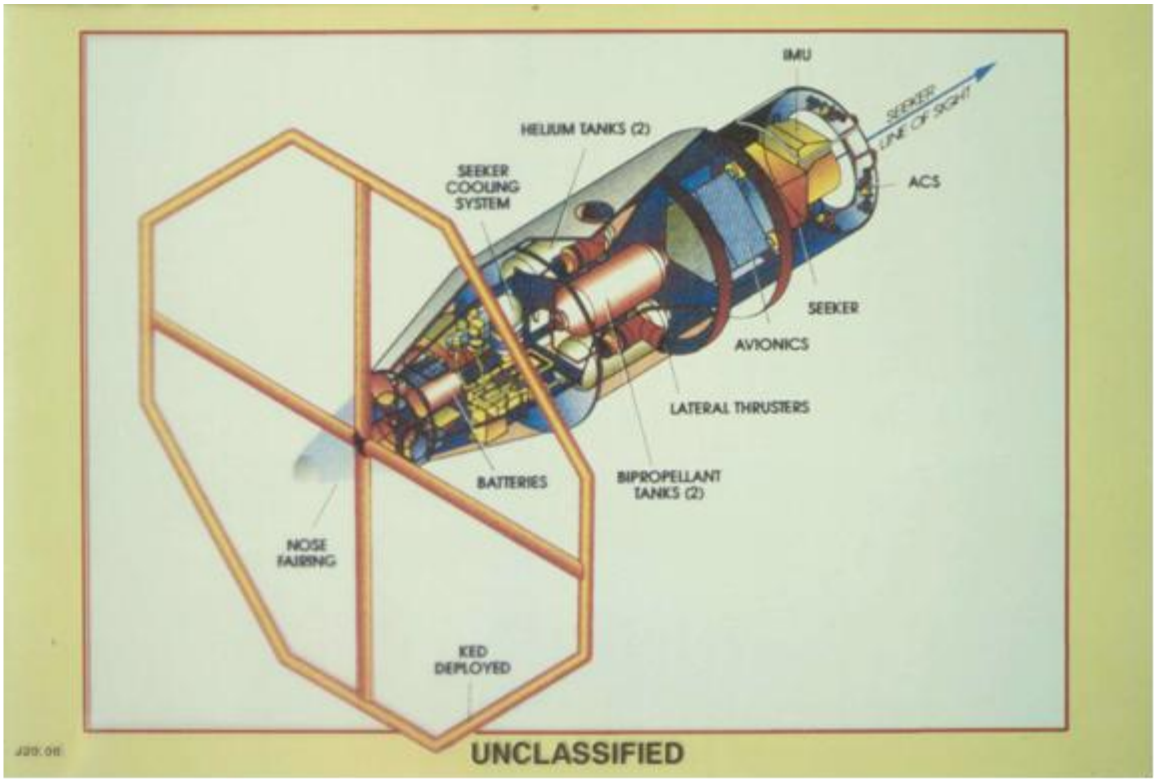

FIGURE 5-7 Exoatmospheric Re-entry Interceptor Subsystem (ERIS) KKV configuration showing enhancement device concept in the deployed position. SOURCE: David K. Barton, Roger Falcone, Daniel Kleppner, Frederick K. Lamb, Ming K. Lau, Harvey L. Lynch, David Moncton, et al. 2004. *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues,* American Physical Society, College Park, Md., October 5, p. S207.

RECOMMENDED GMD EVOLUTION—THE SENSORS

Layered defense systems are desirable to increase engagement effectiveness, but individual layers should be implemented only if the value added is better and more cost effective than competing options. Layered defense is commonly thought of as independent multilayers of distinctly different elements that make up the individual layers. However, it is more useful to think of layered defense as multiple SLS engagement opportunities over a large portion of an ICBM threat trajectory.[4] This should include multiple layers of sensors that support the engagements of the interceptors. Many of these multiple layers of sensors may be in the same configuration, but they may be based in different geographical areas to provide coverage and engagement flexibility to engage ICBM threats over a wide range of approach azimuths.

The threat detection, tracking, and imaging sensor suite is a key element of any missile defense system, as described earlier in the recommended concept of operations. Early threat detection and track with sufficient accuracy to provide targeting of long-reach defensive missiles is essential for engagements with a high probability of success. The sensor suite includes the sensors on the interceptor as well as active and passive off-board sensors with a diversity of basing. Owing to the size and power requirements, most of the active long-range radars will have to be land- or sea-based. The passive sensor suite is made up of infrared sensors operating in the short-range infrared (SWIR) to LWIR wave bands, which can be deployed on airborne, missile-borne, or satellite platforms. The deployment configuration should provide early threat detection and track from multiple sensor sources—preferably combinations of active and

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[4] SLS can include both shoot and look at the intercept before firing again and an equally valuable case of looking at what the first interceptor sees and designates to home on and dispatching another interceptor if there appears to be more than one credible object ranked.

passive—with capability for continuous coverage over large segments of the threat trajectory. The system sensor suite should be configured to avoid single-point sensor failure that would disable the system. Such failure would include mechanical failure and downtime for repairs and maintenance as well as failures due to various natural phenomena such as weather, storms, solar activity, and ionospheric perturbations. It would also include covert and overt actions by adversaries. Redundancy of sensors is another form of layering. If the sensors are chosen judiciously, this can be done at a reasonable cost.

GMD-E Radars

The recommended GMD-E deployment takes advantage of the space-based SBIRS and DSP satellite systems, as well as currently planned forward-based AN/TPY-2 radars, referred to as standalone X-band radar (FBX), located in Japan and at one or more locations north of Iran.

In addition, the recommended GMD-E provides a significant enhancement in land-based radars through the introduction of a recommended doubling of existing AN/TPY-2 radars, one stacked on top of the other. These doubled (or stacked) radars would be mounted on azimuth turntables (like the sea-based X-band radar (SBX)) that could be mechanically reoriented (not scanned) through an azimuth sector of ≈270 degrees. For the purposes of this report, the recommended doubled AN/TPY-2 radars are designated GBX radars.

More specifically, the recommended GBX radars would provide electronic scan coverage from the horizon to the zenith over a traverse angle sector of ±45 degrees from broadside. The traverse is a great circle angle passing through the broadside azimuth at the elevation of the scanned beam it covers: For example, ±45 degree azimuth at the horizon, ±93 degree azimuth at 45 degree elevation, and all azimuths at zenith.

The output of this “doubled,” over-and-under, dual-array GBX system would be combined coherently through a time-delay device that permits the full instantaneous signal bandwidth to be used for range Doppler imaging. The coherent combination produces an elevation beam width half that of the AN/TPY-2 radar, with twice the gain (four times the two-way gain) and twice the peak and average power. Duplicate power supply and cooling units would be required, but a single electronic equipment unit should suffice, with minimal added electronics to handle the combined signals.

It is recommended that these stacked GBX radars be located at the current UEWR (ballistic missile early warning system (BMEWS)) sites (Cape Cod, Massachusetts; Grand Forks, North Dakota; Thule, Greenland; and Fylingdales, United Kingdom). Additionally, as a result of its analysis, the committee recommends that a fifth GBX radar be added at Clear, Alaska, and that the SBX be moved permanently to Adak, Alaska.

Figure 5-8 shows the GBX architecture for homeland defense that was used for the analysis to support a multiple SLS firing doctrine: This architecture greatly increases system engagement effectiveness. Note in Figure 5-8 that the field of regard for the AN/TPY-2 radars is shown symbolically as 360 degrees. In fact, a rotational mounting would be needed to accomplish this 360-degree capability.

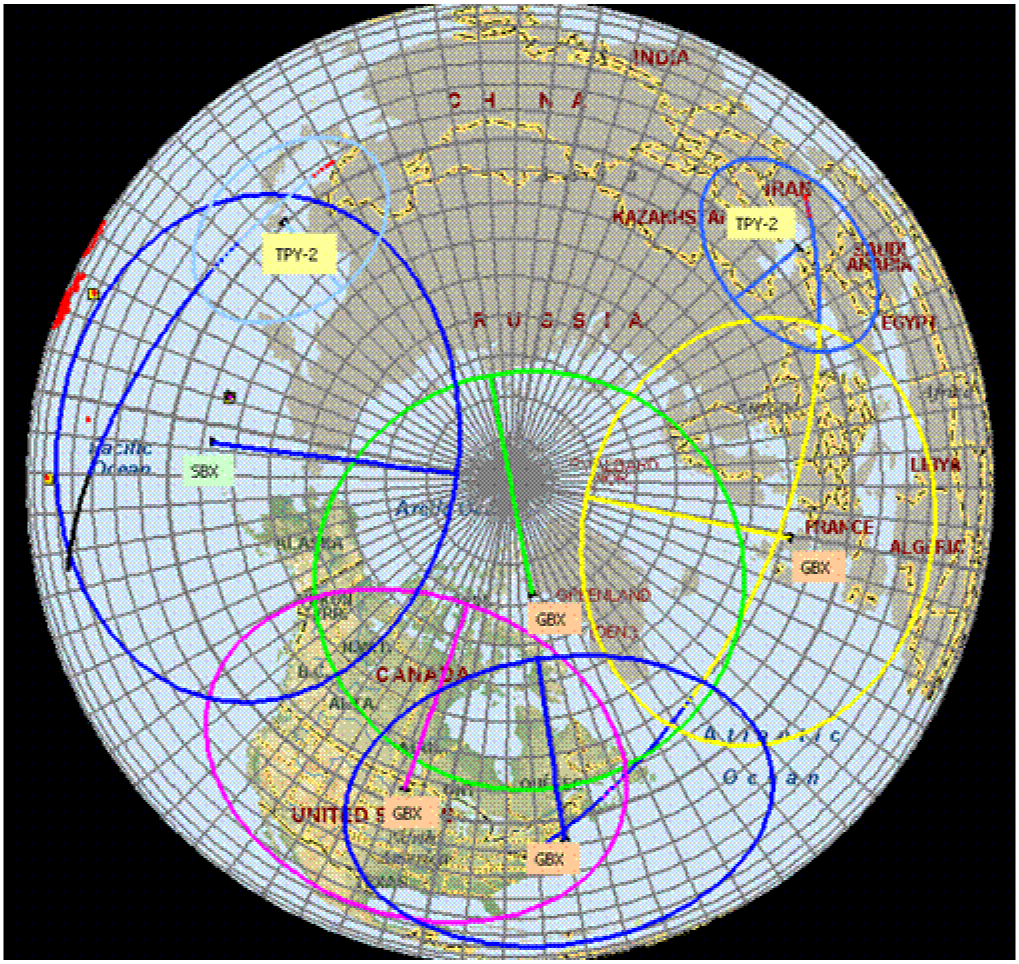

FIGURE 5-8 Recommended notional GMD-E radar architecture for homeland defense.

Scheduling of X-Band Radar for Multiple Engagements

The range at which acquisition and tracking of a target complex is possible can be increased when accurate cueing from external sensors permits the X-band radars to be pointed at the target without use of an acquisition scan. This allows the integration of multiple pulses. Without regard to the transmitted waveform, the time required to exchange a pulse with a target at 1,000 km range is equal to twice the range divided by the velocity of light, which is ≈7 ms, plus an allowance for reception of the entire echo, totaling ≈8 msec. For example, if integration of 10 pulses for acquisition and tracking were necessary, a beam dwell of approximately 80 msec at 1,000-km target range, or 160 msec at 2,000-km target range would be required. Accurate velocity measurement and range-Doppler imaging would typically require a sequence of these 10-pulse dwells over a period of approximately10 sec (for example, 4 dwells at 2.5 sec intervals). Thus, each target would consume a nominal 320 – 640 msec in 10 sec, or 3.2 – 6.4 percent of the radar’s time.

An uplink/downlink function should be included as a new radar mode. Assuming that the transmitter and receiver could be modified to pass the required information, this function is estimated to require 0.65 percent of the radar resources per interceptor for an in-flight target update (IFTU) every 10 sec, until the final 10sec before intercept, where 65 percent might be required for IFTUs every 0.1 sec (classified Appendix J provides greater detail). In the unlikely event that two or more interceptors intercept within 10 sec of each other, they would have to share the resources and accept less frequent IFTUs.

Therefore, combined tracking and IFTU activity in the example above would requireapproximately 4-7 percent of the radar resources per target until 10 sec before intercept, corresponding to a radar system that could handle approximately 14-26 simultaneous targets, depending on their distance from the radar. The resource allocation is roughly proportional to the average target range.

The kill assessment function requires minimal radar resources, as it serves merely to detect the fragmentation of the selected target by the interceptor. If the prior discrimination has ruled out the presence of additional lethal targets, fragmentation of the selected target is confirmation of kill.

The very-long-range sea-based X-band radar (SBX) currently being used as a test asset would provide Pacific coverage based in Adak, Alaska, where moorings for it currently exist. It is shown with 360-degree coverage because it is turntable mounted, but its array has a limited field of view. Additionally, two medium-range AN/TPY-2 class X-band radars deployed in Japan and southeastern Europe (eastern Turkey) provide the precision tracking capability and kill assessment to enable SLS with the concurrent viewing that the committee described earlier. These radars, coupled with the recommended GMD-E interceptors, provide SLS engagement battle space over virtually all populated portions of North America for the midcourse phase of the ICBM threat trajectory—i.e., they provide homeland defense.

Details of the analysis (a homeland defense-oriented analysis process) utilizing radars and radar deployment presented above are presented in the next section.

RESULTS OF ENGAGEMENT ANALYSIS AND SIMULATION OF THE SYSTEM IN DEFENDING THE HOMELAND

Overview

This section summarizes the results of detailed engagement analyses used to assess the effectiveness of the recommended GMD-E for the missions for homeland defense against any limited attack: Iranian and North Korean threats were used as cases for analysis. In each case provided below, interceptor basing was assumed at FGA, and at a northeast CONUS location, e.g., Fort Drum, New York; Caribou, Maine; or Rome, New York. An additional trial location at Grand Forks, North Dakota, was also evaluated but found redundant and unnecessary.

Coverage of GMD Evolution Against Threats from Iran

The following section considers threats from Iran and compares single-shot and SLS coverage for minimum-energy, lofted, and depressed trajectories.

Figure 5-9 shows the maximum footprint where only one shot is possible in blue using the committee's proposed architecture for homeland defense. It also shows the footprint for at least one SLS cycle in red.[5] Interceptors are assumed to be launched 10 sec after entering an X-band radar's track capability and must be observed by X-band radars for at least 50 sec.

Here, the Alaska site and the northeast site provide full coverage of the United States and Canada for at least one shot, and there is SLS capability over all populated areas of North America. In addition, in the area between the single-shot footprint and the SLS footprint, there is battle space for second shots to replace failures or to engage additional credible objects identified by the first interceptor at the time it designates its intended target object. This feature is sometimes called shoot-evaluate-shoot or shoot-designate-shoot. The bottoms of the footprints are left open because they depend on the threat missile maximum range assumed. Because the footprints are the union of overlapping coverages from FGA, and, in these examples, from Fort

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[5] Figures 5-8 to 5-14 were generated from the committee's analysis using Google Earth. ©2011 Google, Map Data©2011 Tele Atlas.

FIGURE 5-9 Notional single-shot and SLS footprints against minimum energy ICBM trajectories from Iran.

Drum, New York, the overlapping boundaries of each site are shown in the same color, but dotted.

At anything less than maximum range, the threat could use the excess energy to fly a lofted or depressed trajectory if such a trajectory offered any advantage. The next two figures show single-shot and SLS footprints for coverage against those tactics.

Figure 5-10 again shows complete coverage of North America on a single-shot basis, with the red footprint showing that all populated areas are within the SLS footprint. Depressed trajectories drive the leading edge of the footprint coverage back, as shown in Figure 5-11. The time constraints, and the fact that the forward radars see less of the trajectory or are underflown completely, significantly reduce the coverage for a guaranteed SLS footprint; even here, however, the single-shot coverage is complete except for the North Slope of Alaska.

The main message of the figures and the associated assessment is as follows: If the recommended CONUS-based GMD-E interceptor is adopted, there is no need for early intercepts from Europe to help defend North America, because the CONUS-based interceptors provide excellent coverage with at least one SLS engagement and often a third shot as well.

Early Intercept: Useful or Not?

In view of the above message regarding early intercepts vis-à-vis the recommended GMD-E, some additional discussion of early intercepts is useful. In general, the value of early intercept depends on the fragility or robustness of the CONUS deployment of GMD, including the recommended GMD-E. The contribution of early intercepts using the GMD-E interceptor in Europe and the western Pacific was studied as part of the committee’s analysis, and examples are shown later in this chapter and in more detail in classified Appendix J. However, at the present point, some general observations may be made.

FIGURE 5-10 Notional defense footprints: Iran lofted trajectories.

FIGURE 5-11 Notional defense footprints: Iran depressed trajectory.

In reviewing Figure 5-11, it can be seen that there is only single-shot coverage of the Canadian Maritimes and Newfoundland. Figure 5-12 shows how the coverage changes with a 4.5 km/sec interceptor at the Polish site; this extension of the red SLS boundary is shown in yellow. While that interceptor can be overflown by modest lofting, it provides an additional early shot against minimum-energy or depressed threats from Iran to the East Coast of North

FIGURE 5-12 Notional coverage against depressed threats (notional 4.5 km/sec interceptor at the Polish site).

America that would otherwise be defended only by single-shot coverage. The same increase in coverage would result against minimum-energy threats toward northeast Canada. The other potential advantage of early intercept is to force an adversary to deploy missile payloads more quickly, which may complicate its ability to deploy effective countermeasures. However, as shown in some of the engagements analyzed in this chapter, early intercept even in the best of cases does not occur early enough to avoid the need for midcourse discrimination.

While intercept from Europe would be quite important if nothing is done about the limitations of the current GMD system architecture, the committee believes it is better to solve that problem, and others, with the recommended CONUS-based GMD-E. It notes that a 4-km/sec interceptor based in either Romania or northern Poland does not have sufficient reach to engage threats headed to the United States from Iran. While the introduction of the GMD Evolved Interceptor into Poland in a later phase of the adaptive deployment would avoid the cost of yet another interceptor development, it would clearly exacerbate political tensions in the region: It would be able to intercept Russian ICBMs deployed in the southwesternmost Russian bases heading toward targets in the eastern United States. The added shot opportunities provided by introducing a Poland-based GMD-E interceptor are shown later in this chapter. A 4.5-km/sec interceptor cannot threaten any Russian strategic deterrent. While a 6-km/sec interceptor in Europe would provide additional shot opportunities for CONUS defense, the committee does not advocate introducing an interceptor with fly-out velocity greater than about 4.5 km/sec into Europe.

Coverage of GMD Evolution Against Threats from North Korea

In a format similar to that of the figures showing the threat from Iran, Figures 5-13, 5-14, and 5-15 compare nominal single-shot and SLS coverage for minimum energy, lofted, and depressed trajectories from North Korea for the committee’s recommended architecture. These threats are seen before burnout by the Shariki FBX, then by the SBX at Adak, Alaska, and finally, in some cases, by the GBX at Clear, Alaska.

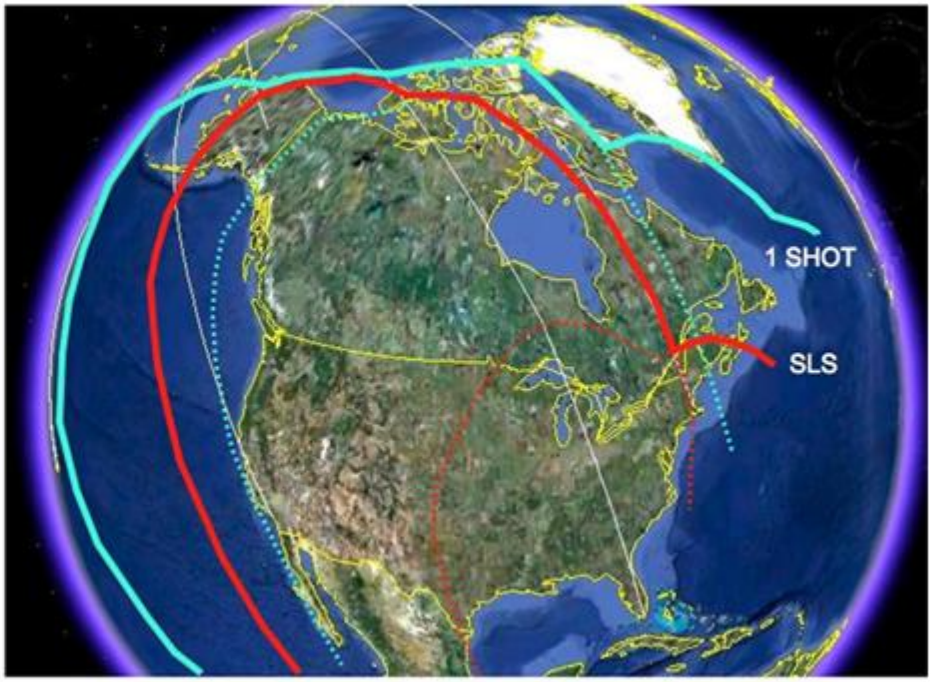


FIGURE 5-13 Notional defended footprint of North Korean minimum energy trajectories.

FIGURE 5-14 Notional defended footprint of North Korean lofted trajectories.

FIGURE 5-15 Notional defended footprint of North Korean depressed trajectories.

Figure 5-12 shows the notional single-shot footprint in blue against minimum-energy threats from North Korea. In these cases, threats are first tracked by the Shariki FBX for over 100 sec and then by the SBX at Adak, Alaska, and in some cases by the GBX at Clear, Alaska. The coverage afforded by lofted trajectories from North Korea is shown in Figure 5-14. The two sites easily provide SLS coverage of all of North America against lofted threats from North Korea. Figure 5-15 shows the coverage against North Korean depressed trajectories. Here, while most of northwest Canada is protected, but the coverage of Alaska is reduced by the short time of flight and the shallow trajectories, making defense of the FGA site less robust than might be desired.

It should be noted, however, the committee's analysis shows that notional interceptors with a fly-out velocity of 4.3-4.5 km/sec that are ship-based in the northern Sea of Japan with engage-on-remote capability from the Shariki FBX would be capable of an additional early shot for North Korean threats to Alaska.

Layered Interceptors

Layered sensors with the ability to provide almost continuous ICBM target track from launch to near impact give rise to layered deployment interceptors. Using the sensor configuration discussed above, a hypothetical interceptor basing concept is added to examine the propects of developing a layered missile defense system capable of SLS engagements in all phases of the ICBM trajectory, from early ascent to near apogee and beyond apogee to near the bottom of the battle space at reentry. An important attribute of a layered system of this type includes a provision for downlinking the data from the interceptor sensor as it closes on the target. The in-flight interceptor communication concept is presented in classified Appendix J. This then gives the interceptor a dual role as another layer in the sensor suite, with the most accurate and current data available for use by successive interceptors in the SLS sequence.

Interceptor Site Additions Considered

In addition to FGA and VAFB, new sites, including a northeastern United States site such as Fort Drum, New York, or northern Maine; a far western site on Shemya, Alaska; and a European site in Poland, were studied. All of these new interceptor sites were assumed to be populated with the new GMD-E high-performance interceptors, as previously described, with communication links to the BMC2 system. In this regard, the first step in a deployment evolution (using GMD-E interceptors) would be a committee-recommended site for 30 interceptors in upstate New York or northern New England. The next step in the evolution would be a phased upgrade of the current interceptors at FGA and VAFB, with the new GMD-E interceptors. In addition, an Aegis system would be used to defend Hawaii (either a ship positioned near Kauai, Hawaii, or Aegis ashore on Kauai with an additional GBX radar and THAAD battery for second shot).

Figures 5-16 and 5-17 and Table 5-3 present hypothetical ICBM threat engagements for scenarios between a Middle East launch point and the East Coast and middle of CONUS. This information is provided as an example of the level of analytical detail that was incorporated within the study process. Similar data are provided in classified Appendix J for a northeast Asia launch point aimed toward Hawaii, the West Coast, or the middle of CONUS.

This hypothetical ICBM engagement assessment illustrates a firing doctrine using SLS engagements. Additionally, the trajectories in the figures that follow and in classified Appendix J are color-coded to reflect the portions of the trajectories that are being tracked by the various radars. If more than one radar is capable of tracking the threat, the trajectory ground track will have intermittent colors that correspond to the radars involved. The initial red segments of the threat trajectories indicate the booster burn phase that is being tracked by IR satellite sensors. Segments that are shown in black indicate no sensor track. Likewise, the red segments of the interceptor trajectory represent the boost phase at launch and the homing phase that begins at KV sensor acquisition of the threat complex.

From the hypothetical engagement examples provided below, the engagement battle space flexibility available in this layered concept is shown to be significant to a wide range of threats and countermeasures that are mission-timeline-sensitive in design; it also provides for greater flexibility to overcome early engagement component failures of our system (e.g., radar outages).

This analysis represents a reasonably thorough conceptual analysis of hypothetical threats and is by no means optimized to achieve a good balance among the sensor and interceptor elements. Such a balance would require a much more rigorous and broader-ranging assessment of parametric technical requirements and an evaluation of system design. However, the committee believes the analysis presented below can point the way to a layered missile defense concept that will be very effective and highly responsive to the changing strategic environment and to the uncertainties surrounding who our adversary might one day be.

Middle East Threat to CONUS East Coast

Figures 5-16 and 5-17 show two different views (a ground track view and a three-dimensional view) of a hypothetical East Coast engagement with at least two SLS opportunities from CONUS-based interceptors, with the first engagement just after apogee. If the same interceptor type were also based in Poland, two additional ascent shots would be possible. Table 5-3 displays an event timeline for this case.

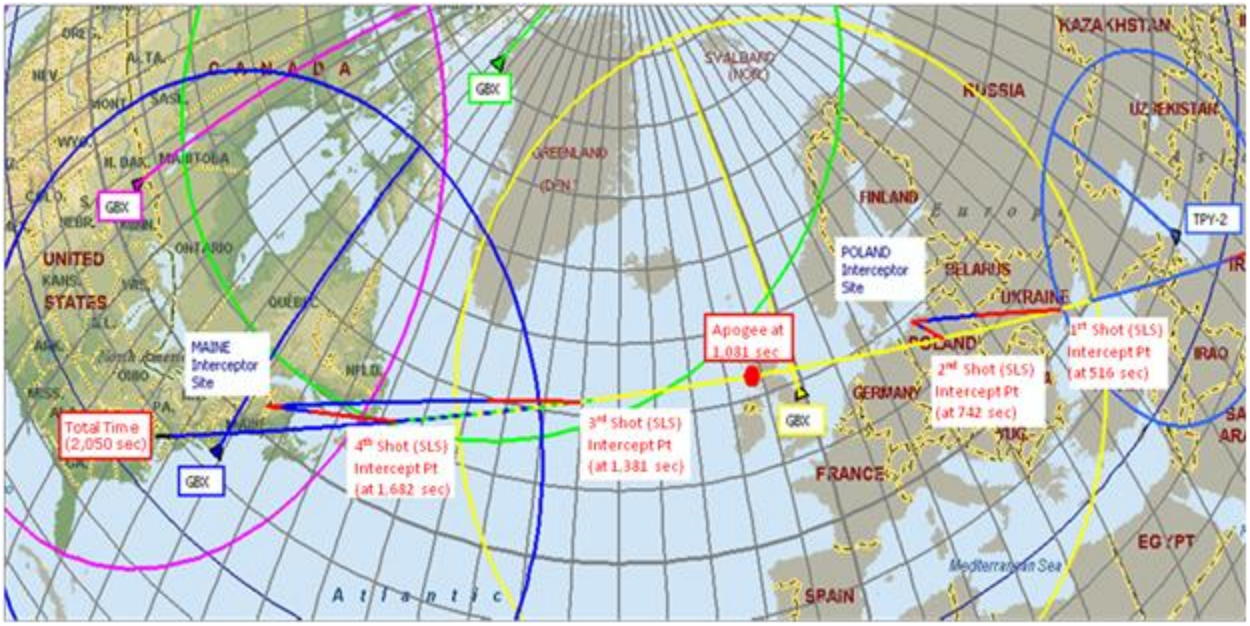


FIGURE 5-16 Example of Middle East to U.S. East Coast four-shot SLS engagement (ground track view).

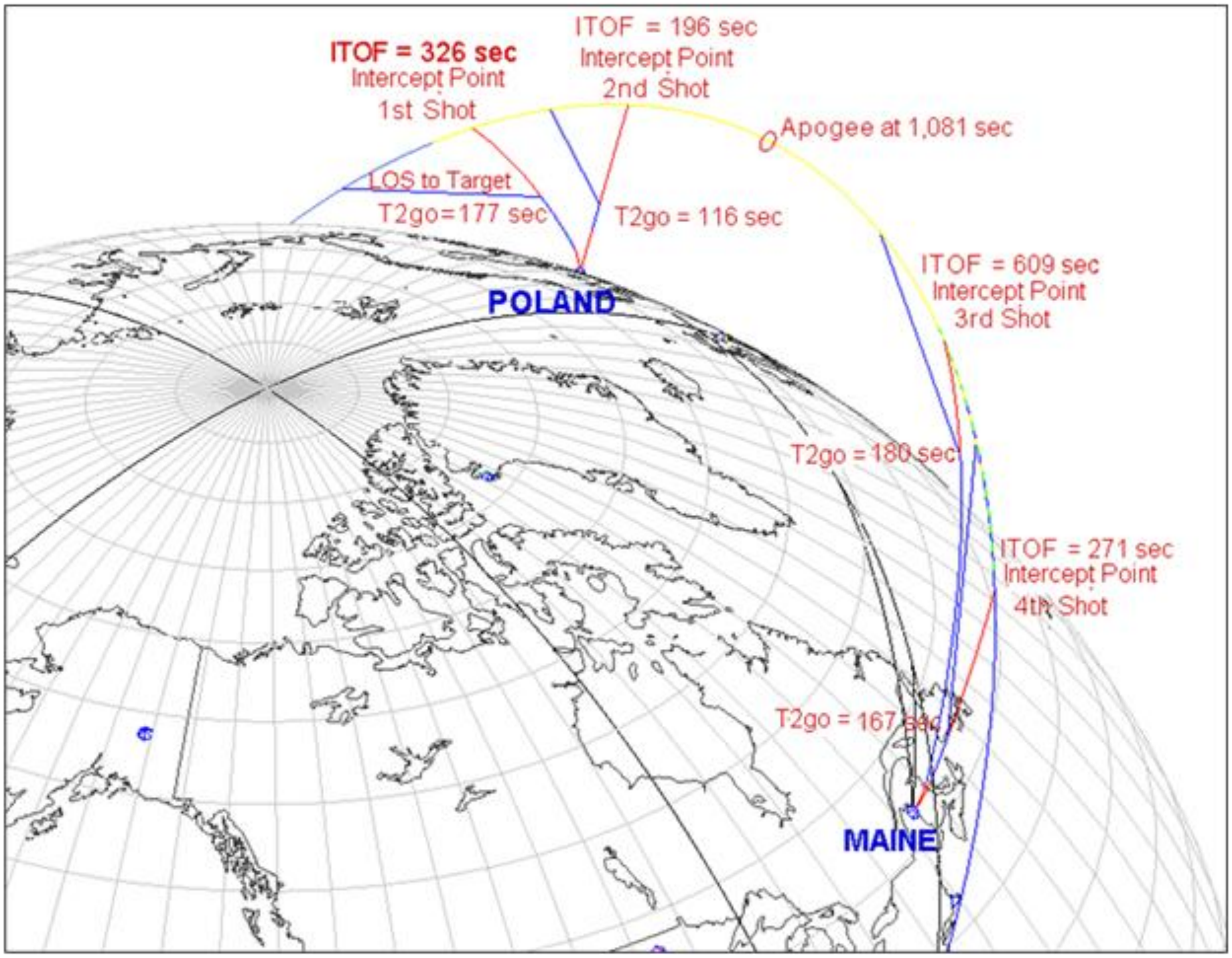


FIGURE 5-17 Example of Middle East to U.S. East Coast four-shot SLS engagement (three-dimensional view).

TABLE 5-3 Typical Mission Timeline

Mission Timeline (sec)	Mission Event Sequence
0	Threat launch
30	Initgial DSP report
125	Begin track Azerbaijan XBR (R = 872km; elev = 2.2 deg)
180	Threat booster burnout
190	First shot interceptor launched from Poland site (commiy on track from Azerbaijan XBR)
260	Interceptor burnout
339	KV sensor acquires threat complex (R2Tgt =1,994 km; TGo = 177 sec; R2Int = 1,061 km
349	Initial course correction divert (R2Tgt = 1,883 km; T2Go = 167 sec; R2Int = 999 km
516	First shot intercept opportunity (Alt = 836 km; R = 1,462 km; ITOF = 326 sec; closing vel 11.3 km/sec; Xang = 36 deg)
	Second shot (SLS) interceptor launched from Poland site (commit on Fylingdales GBX track + TOM from previous KV sensor
	Interceptor burnout
	KV sensor acquires threat complex (R2Tgt = 1,000 km; T2Go = 116 sec; RInt = 692 km)
	Initial optional course correction divert (R2Tgt = 915 km; T2Go = 106 sec; R2Int = 636 km)
	Second shot intercept opportunity (Alt = 1,111 km; FO R = 302 km; ITOF = 196 sec; closing vel = 8.6 km/sec; Xang = deg)
	Kill (hit) assessment by Fylingdales GBX (R = 2,780 km; elev = 6.3 deg)
526	Second shot (SLS) interceptor launched from Poland site (commit on Fylingdales GBX track + TOM from previous KV sensor
616	Interceptor burnout
626	KV sensor acquires threat complex (R2Tgt = 1,000 km; T2Go = 116 sec; RInt = 692 km)
636	Initial optional course correction divert (R2Tgt = 915 km; T2Go = 106 sec; R2Int = 636 km)
742	Second shot intercept opportunity (Alt = 1,111 km; FO R = 302 km; ITOF = 196 sec; closing vel = 8.6 km/sec; Xang = deg)
752	Kill (hit) assessment by Fylingdales GBX (R = 2,780 km; elev = 6.3 deg)
772	Third shoht (SLS) interceptor launched from Caribou (commit on Fylingdales GBX track + TOM from previous KV sensor
842	Interceptor burnout
1,081	Threat reaches its trajectory apogee
1,201	KV sensor acquires threat complex (R2Tgt = 1,992 km; T2Go = 180 sec; R2Int = 985 km
1,211	Initial optional course correction divert (R2Tgt = ,882 km; T2Go = 170 sec; R2Int = 929 km)
1,381	Third shot intercept opportunity (Alt = 1,144 km; R = 2,770 km; ITOF = 609 sec; closing vel = 11.1 km/sec; Xang = 8.4 deg)
1,391	Kill (hit) assessment by Fylingdales (R = 2,382 km; elev =nm19/4 deg)
1,411	Fourth shot (SLS) interceptor launched from Carib ou (commit on Fylingdales GBX track + TOM from previous KV sensor
1,481	Intercept burnout
1,515	KV sensor acquires threat complex (R2Tgt = 1,998 km; T2Go = 167 sec; R2Int = 1,031 km)
1,525	Initial optional course correct divert (R2Tgt = 1,879; T2Go = 157 sec; R2Int =m,967 km)
1,682	Fourth shot intercept opportunity (Alt = 780 km; FO R = 1,174 km; ITOF = 271 sec; closing vel = 12 km/sec; Xang = 16 deg)
1,692	Kill (hit) assessment by Cape Cod GBX (R = 1,870 km; elev = 16.6 deg)
	Battle space remaining = 319 sec
2,021	Threat reaches minimum intercept altitude if not intercepted
2,050	Threat reaches target if not intercepted

NOTE: Hypothetical Middle East to East Coast CONUS four-shot SLS scenario. R, range.

Figure 5-16 displays the intercept event times for each shot in the four-shot SLS sequence and the apogee point looking down along the ground track of the threat trajectory. In this example the first two shots are taken from the Poland interceptor site prior to apogee. The first shot, if it misses or sees more than one credible object, can be considered as a pathfinder for the second shot in the SLS firing doctrine. Likewise, this discrimination data stream cascades downward to each succeeding shot in the SLS sequence. The continuous ground-based radar (GBR) track and hit/kill assessment data along with data from the earlier interceptor sensor TOM are fused by the BMC2 and provided to each interceptor in the SLS succession until a kill is assessed as complete or until the battle space is exhausted. The last two shots, if needed, come from a CONUS East Coast interceptor site, in this example at Caribou, Maine.

Figure 5-17 displays the same engagement using a three-dimensional projection to give an altitude perspective along with additional data indicating the geometry between the line-of-sight (LOS) at the KV sensor acquisition of the target complex and the time to go (T2Go) to intercept of the target. The interceptor total time of flight (ITOF) from launch to intercept of the target is also shown. The divergent blue line is the LOS to the target, and the red line is the path of the interceptor KV to the target. The angle at which the KV trajectory (red) approaches the target trajectory (yellow) gives an indication of the crossing angle between the KV and target. Crossing angles of less than 90 degrees result in head-on intercepts, and crossing angles greater than 90 degrees are referred to as tail-chase intercepts. Head-on intercepts are preferred due to their higher closing velocity, which results in much greater energy exchange between the colliding bodies and therefore a much more lethal engagement.

Table 5-3 presents a more detailed timeline and provides metrics for an engagement such as this. It can be seen from an examination of the event timeline that a significant battle space is left after the fourth shot in the SLS engagement sequence. This provides a lot of flexibility in the timing of the actual shots and allows more time for certain functions that might be impacted by natural backgrounds and unexpected events during the course of the engagement. For example, when the first interceptor first acquires the threat complex at 339 sec and tracks long enough to determine that there is more than one credible object in the threat, this TOM information can be transmitted back to the BMC2 and an additional interceptor(s) can be launched before the first interceptor to make its intercept. This strategy is referred to as shoot-engage-shoot (SES) and can make use of the approximately 150-160 sec of battle space available before the first interceptor reaches its intercept point. Likewise, if the first interceptor should fail at any point in its flight, and this information is available to the BMC2, it can be replaced immediately by another interceptor using a strategy referred to as shoot-fail-shoot (SFS).

Effect of Time Delays Between Planned SLS Engagements

If the second shot is taken at its normal planned time, based on SLS, it would be launched at 546 sec and would intercept at 742 sec in the mission timeline. This assumes a 30-sec time delay for XBR tracking and kill assessment between the first intercept and launch of the second interceptor. Kill assessment is based on real-time analysis of X-band radar track and debris data to determine if a credible threat on a continuing ballistic path survived and should be engaged. It is noted that the closing velocity for the second intercept is about 8.6 km/sec and the crossing angle is about 81 degrees, with a total time of flight from launch to intercept of 196 sec at a fly-out ground range of only 302 km. Additional analysis shows the second interceptor launch could be delayed by as much as 2 min (120 sec), at 666 sec in the timeline, and still engage the target with a closing velocity of about 4.8 km/sec and a crossing angle of 127 degrees (a tail-chase geometry) at 931 sec in the mission timeline compared to the 742 sec in the normal sequence. When analysis is taken to the kinematic limit of being able to engage with the second shot, it shows the maximum additional delay between the first intercept and launch of the second interceptor is 3 min (180 sec), resulting in a second interceptor launch at 726 sec and an intercept at 1,353 sec. This results in a closing velocity of only 1.7 km/sec and a crossing angle of 165 degrees (a severe tail chase) and may not have enough closing velocity to effect a lethal collision with the target.

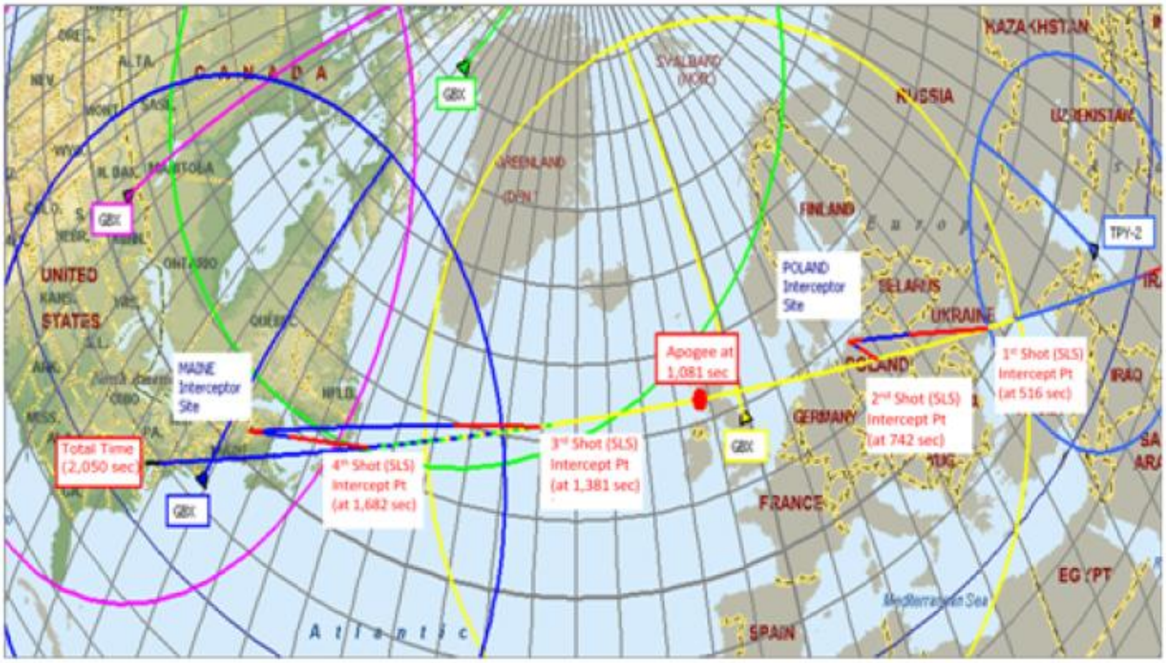
Interceptor SFS Replacement in Each Layer

The timeline that results if this additional 120-sec interceptor launch delay is flowed down to each layer of the four-shot SLS sequence can be compared with the timeline of Table 5-3.

Sequence	Launch (sec)	Intercept (sec)	Closing Velocity (km/sec)	Crossing Angle (deg)
First shot	190	516	11.3	35.7
Second shot	666	931	4.8	127.0
Third shot	1,081	1,525	11.5	10.3
Fourth shot	1,675	1,811	12.2	34.2

Figure 5-18 displays the ground track view of the baseline engagement (same as Figure 5-16) and compares it with the case of 120-sec additional time delays between intercept and launch of each remaining interceptor in the four-shot SLS sequence. In short, if the second interceptor is launched in a normal SLS sequence and there is a failure during boost phase or even a KV sensor failure at target acquisition, at 626 sec into the mission timeline, there is still ample time to launch a replacement interceptor in an SFS mode and not eliminate the downstream opportunities for the third and fourth shots in a continuation of the SLS sequence. In fact, were this same kind of interceptor failure to occur at each layer in the four-shot sequence there still would be enough battle space in each layer for an SFS replacement, as shown in the bottom part of Figure 5-18.

BASELINE ENGAGEMENT



ADDITIONAL 120 SECOND SLS LAUNCH DELAY

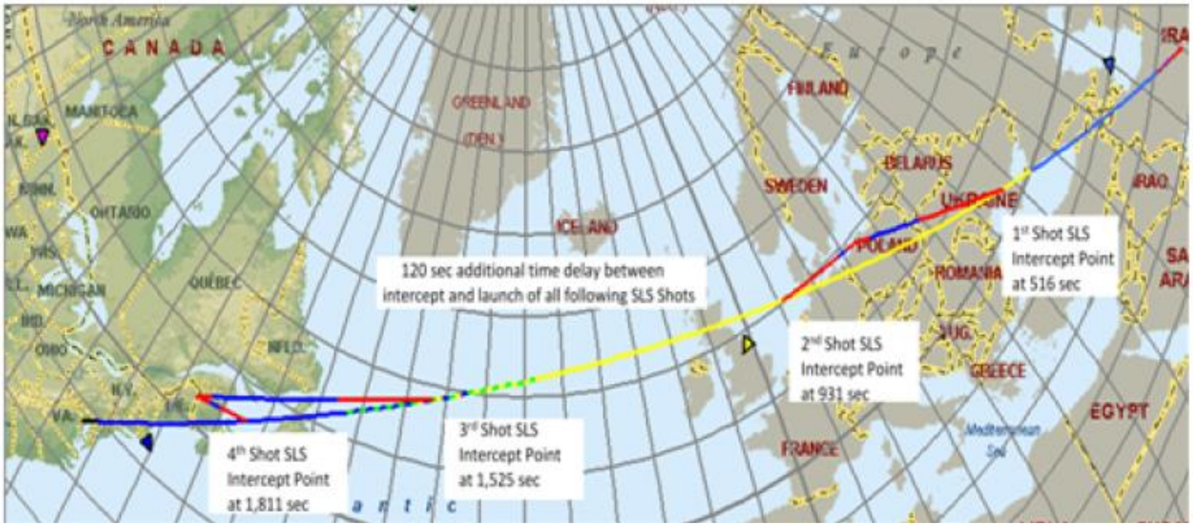


FIGURE 5-18 Example of Middle East to CONUS East Coast four-shot SLS engamement scenario (ground track view).

Effect of Individual and Multiple Radar Outages on SLS Performance

The issue of radar outage is a likely source of single-point failure in a missile defense system. However, with proper layering of critical radars, the concept is very resilient to the loss of one, two, and even three radars. Using an approach similar to that in the interceptor failure example, the result of losing one, two, or three of the four X-band radars at play in this scenario—Azerbaijan TPY-2 (XBR); Fylingdales, U.K. (GBX); Thule, Greenland (GBX); and Cape Cod, Massachusetts (GBX). The Azerbaijan TPY-2 FBX could just as well have been placed in eastern Turkey for the purposes of this analysis.

Single Radar Out

- *Case 1, Figure 5-19.* Azerbaijan out (earliest first-shot commit): Fylingdales GBX fills this role with the following result (can still get four shots, one from Poland and three from Maine):

Sequence	Site	Launch (sec)	Intercept (sec)	Closing Velocity (km/sec)	Crossing Angle (deg)
First shot	Poland	474	690	9.5	67.4
Second shot	Poland	Not enough battle space for second shot Poland site			
Second shot	Maine	720	1,357	11.1	8.3
Third shot	Maine	1,387	1,671	11.9	15.3
Fourth shot	Maine	1,701	1,825	12.1	39

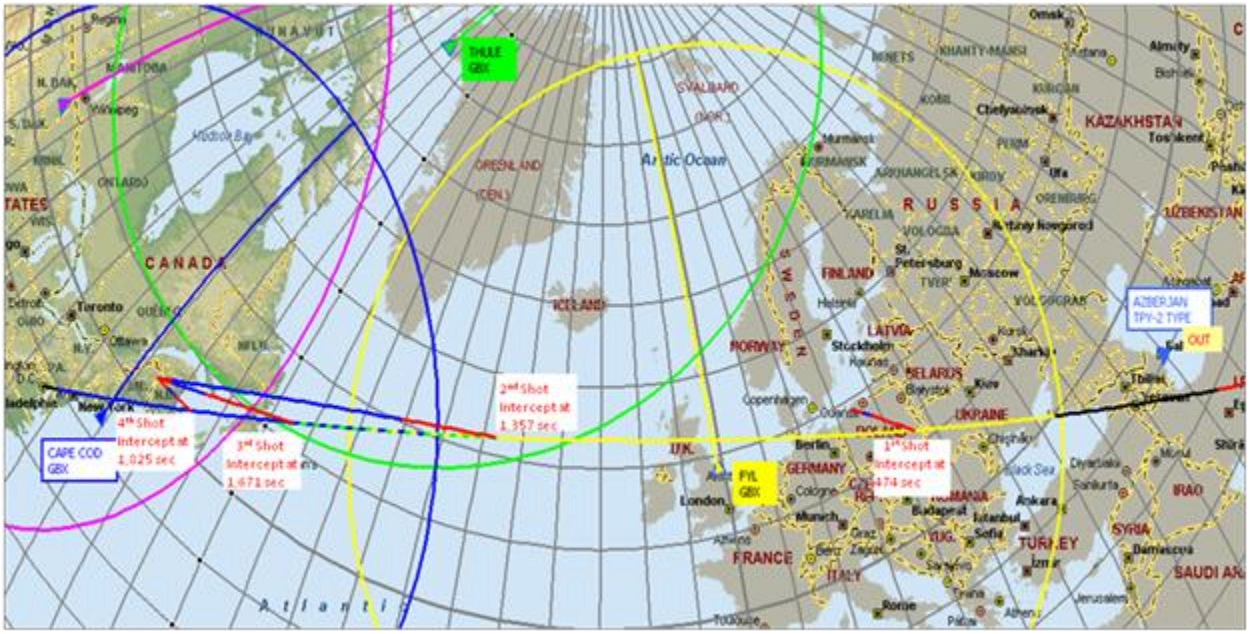


FIGURE 5-19 Case 1: Azerbaijan radar out.

- *Case 2, Figure 5-20 (two possibilities).* Fylingdales out (first-shot kill assessment and second- and third-shot commit).

  —Thule GBX fills the third-shot commit role with the following result:

Sequence	Site	Launch (sec)	Intercept (sec)	Closing Velocity (km/sec)	Crossing Angle (deg)
First shot	Poland	190	690c	9.5	67.4
Second shot	Poland	No radar for first-shot kill KA (use KV TOM and hit/miss report)			
Third shot	Maine	1,373	1,664	11.9	14.9
Fourth shot	Maine	1,694	1,821	12.1	37.5

NOTE: KA, kill assessment.

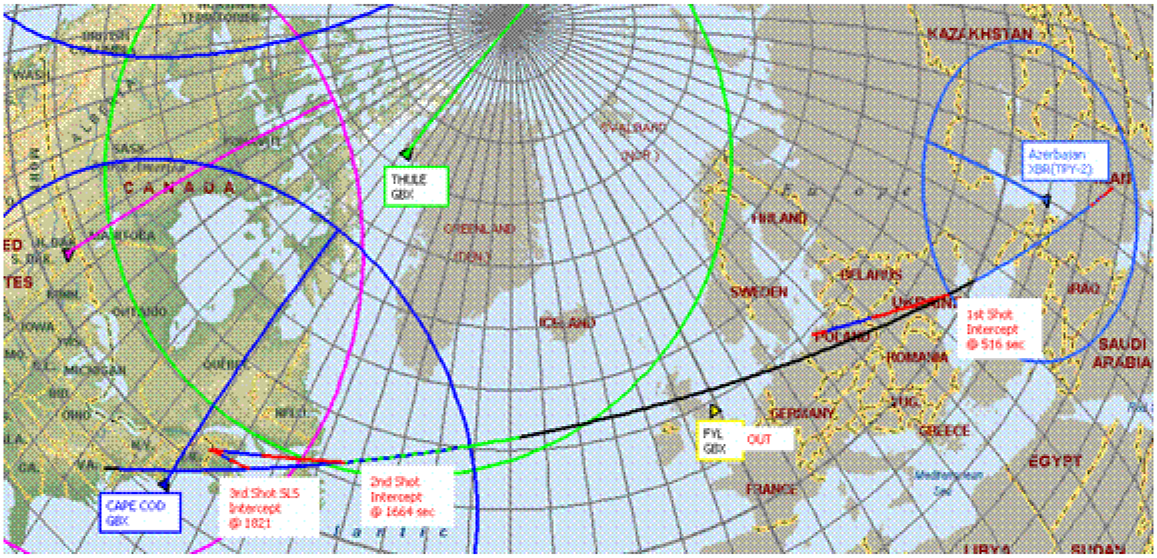


FIGURE 5-20 Case 2: Fylingdales radar out.

—Cape Cod GBX fills the third-shot commit role with the following result:

Sequence	Site	Launch (sec)	Intercept (sec)	Closing Velocity (km/sec)	Crossing Angle (deg)
First shot	Poland	190	516	11.3	35.7
Second shot	Poland	No radar for first shot KA (use KV TOM and hit/miss report)			
Third shot	Maine	1,481	1,716c	12.1	18.5
Fourth shot	Maine	1,746	1,849	11.7	50.3

As shown in the engagement map in Figure 5-20, with the Fylingdales radar out, the second shot comes out of the interceptor site in Maine based on track data from either Thule (launch at 1,373 sec) or from Cape Cod 108 sec later (1,481 sec). This second shot is provided the TOM and hit/miss data from the first interceptor out of Poland even though no radar KA data are available. This second shot is not a true SLS engagement, but it is given significant new data by the BMC2 from the first shot KV sensor combined with the new Thule and/or Cape Cod GBX track data and can be considered an SLS shot. The third shot, if necessary, is a true SLS engagement.

Two Radars Out

- *Case 3, Figure 5-21.* Azerbaijan and Fylingdales radars out: (1) Azerbaijan out (earliest first-shot commit) and (2) Fylingdales GBX out (first- and second-shot commit, third-shot KA). Thule fills third-shot commit role with the following result:

Sequence	Site	Launch (sec)	Intercept (sec)	Closing Velocity (km/sec)	Crossing Angle (deg)
First shot	Poland	No radar for interceptor commit out of Poland (satellite)			
Second shot	Poland	No radar for interceptor commit out of Poland (satellite)			
Third shot	Maine	1,373	1,664	11.9	14.9
Fourth shot	Maine	1,694	1,821	12.1	37.5

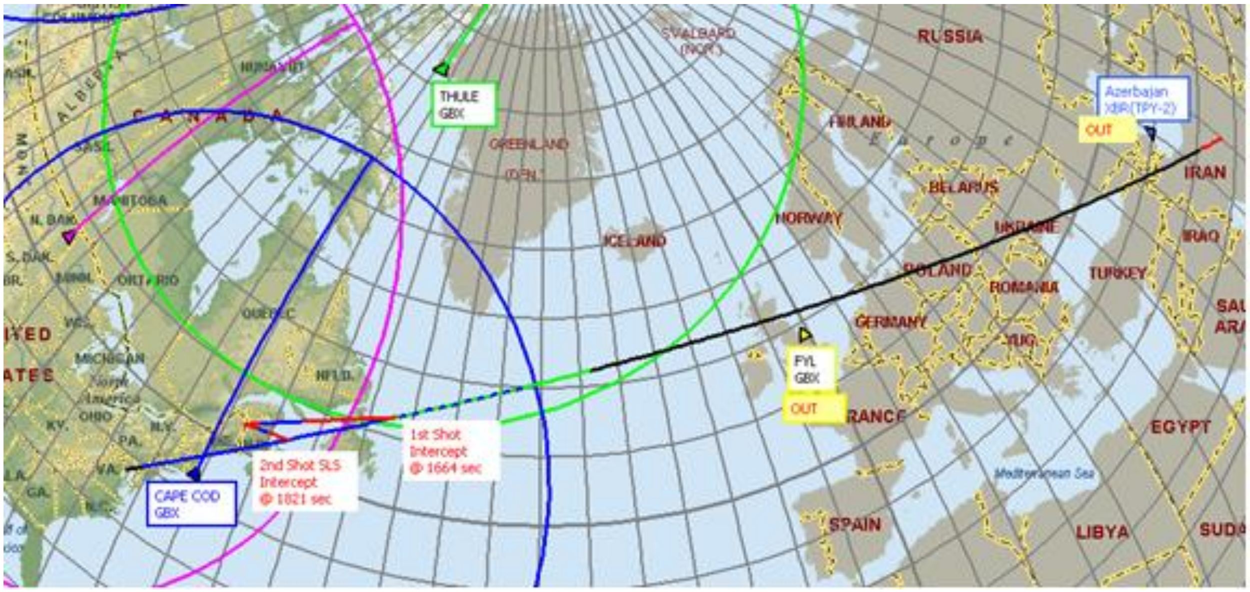


FIGURE 5-21 Azerbaijan and Fylingdales radar out.

Figure 5-21 shows the system rollback to a single SLS capability when both of the forward-based radars are out (Azerbaijan and Fylingdales). In this case the first-shot commit is provided by the Thule GBX radar.

Three Radars Out

- *Case 4.* Azerbaijan, Fylingdales, and Thule radars out: (1) Azerbaijan out (earliest first-shot commit), (2) Fylingdales GBX out (first- and second-shot commit, third-shot KA, (3) Thule out (third- shot commit). Cape Cod fills third shot commit role with the following result:

Sequence	Site	Launch (sec)	Intercept (sec)	Closing Velocity (km/sec)	Crossing Angle (deg)
First shot	Poland	No radar for interceptor commit out of Poland (satellite)			
Second shot	Poland	No radar for interceptor commit out of Poland (satellite)			
Third shot	Maine	1,481	1,716	12.1	18.5
Fourth shot	Maine	1,746	1,849	11.7	50.3

If Azerbaijan, Fylingdales, and Thule are all out, then Cape Cod is left to provide the tracking data necessary for a two-shot SLS engagement very similar to the one just discussed.

FINAL COMMENTS

Chapter 5 is intended to recommend the path forward for the United States to develop the most effective BMD capability—particularly for homeland defense—taking into account the surrounding operational, technical, and cost issues. This will take time, money, and careful testing, but unless this is done, the system will not be able to work against any but the most primitive attacks. The recommended path forward, GMD-E, involves a smaller, shorter burn interceptor configuration building on development work already done by MDA under the KEI program but with a different front end. The heavier, more capable KV with a larger onboard sensor provides the capabilities absent in the current GMD system but responsive to the recommended CONOPS discussed earlier. This evolved GBI would first be deployed at a new third site in the northeast United States along with five additional X-band radars using doubled

THAAD AN/TPY-2 radars integrated together at each early warning system (EWS) site and at Grand Forks, North Dakota. At a later time, the more capable interceptor would be retrofitted into the silos at FGA, with the existing GBIs diverted to the targets program supporting future operational flight tests.

As discussed throughout this report, missile defense is at a critical point. The title of this report, *Making Sense of Ballistic Missile Defense: An Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives*, underscores this critical point and the objectives put forth by both the current and previous administrations. While the current administration will need to consider the 20-yr LCCs associated with present and proposed BMD systems as discussed and assessed throughout this report, it will also need to be mindful of the funding wedge for the next 5 years. Figure 5-22 displays the MDA cummulative annual funding wedge for the FY 2012 future years defense plan (FYDP) submitted by DOD to the Congress. Here, the cumulative total obligation authority (TOA) from FY 2010 through FY 2016 is about $45 billion. It includes approximately $1.3 billion for the precision tracking and surveillance system (PTSS); $1.6 billion for BMC3; and $500 million for advanced technology.

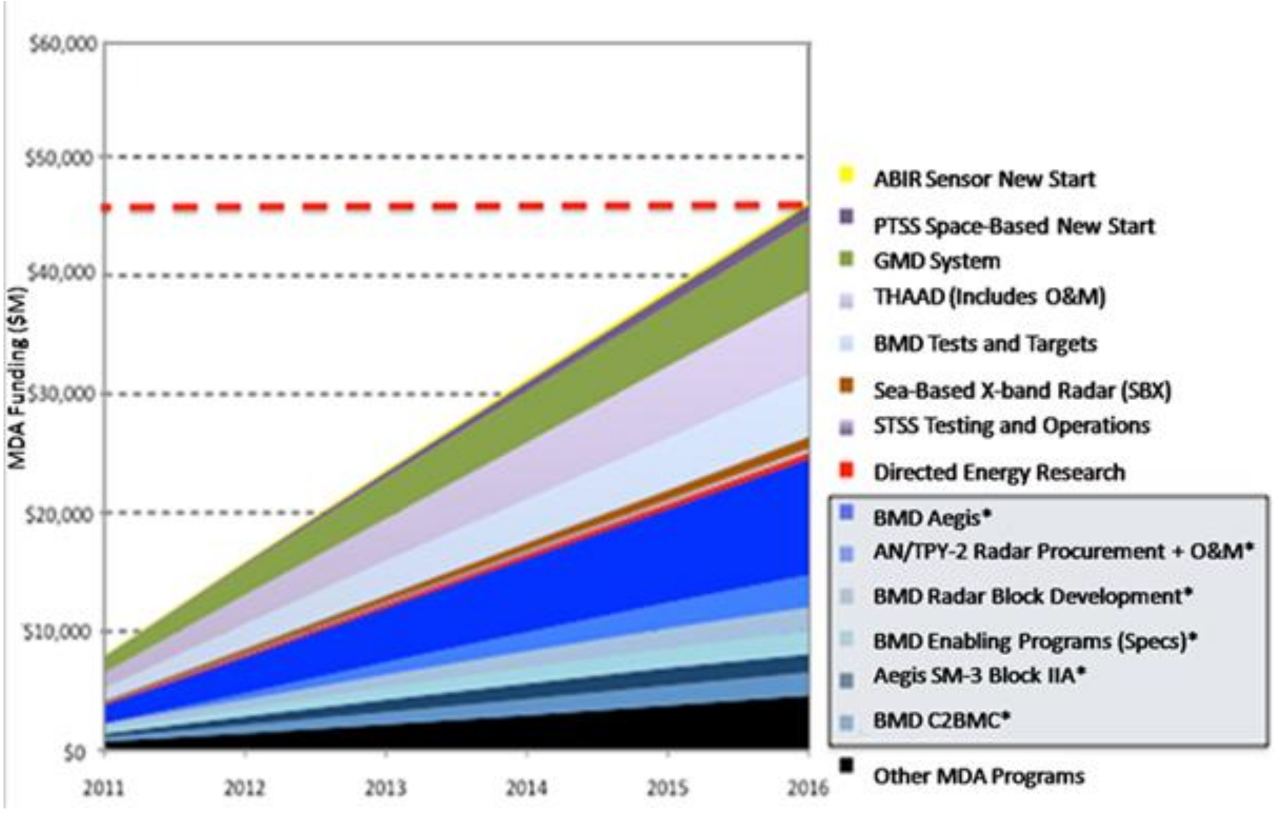


FIGURE 5-22 MDA funding wedge for FYDP submitted to Congress in FY 2011. The activities with an asterisk include funds for PAA Phases I through III.

Based on Figure 5-22 and the results presented in this report, the committee concludes as follows with respect to the immediate future:

1. The current homeland defense plan, which consists of GMD augmented by early intercept capabilities from Europe, is very expensive and has limited effectiveness.
2. PTSS costs four times as much to acquire and four to five times as much over its 20-yr life cycle as the X-band radar suite recommended and it offers less value.
3. GMD-E has substantially lower LCC and provides the most effective capabilities. It can be implemented within the same TOA over the next 5 years with an initial operational capability of FY 2019 provided some low pay-off programs are terminated and others are not started.
4. GMD-E's predicted capability for SLS over most of North America relieves the requirement, necessitated by current GMD limitations, for early intercepts from Europe against threats from the Middle East toward North America. This decoupling allows independent decisions for the later phase of European defense or any other new task.

Unclassified Appendixes

A

Terms of Reference

Section 232 of the Duncan Hunter National Defense Authorization Act for Fiscal Year 2009 (Public Law 110-417) directed the Secretary to Defense to enter into agreement with the National Academy of Sciences (NAS), not later than 90 days after the date of the enactment of this Act, in order to conduct an independent study of concepts and systems for boost-phase missile defense. Specific elements of the study should include the following.

1. Content—the study should include: (a) the extent to which boost-phase missile defense is technically feasible and practical; and (b) whether any demonstration efforts by the Department of Defense of boost-phase missile defense technology existing as of the date of the study (including the Airborne Laser and the Kinetic Energy Interceptor) have a high probability of performing a boost-phase missile defense mission in an operationally effective, suitable, and survivable manner.
2. Systems to be examined—the study should include: (a) the Airborne Laser; (b) the Kinetic Energy Interceptor (land-based and sea-based options); and (c) other existing boost-phase technology demonstration programs.
3. Factors to be evaluated—the study should include: (a) technical capability of the system against scenarios identified in paragraph (4) below; (b) operational issues, including operational effectiveness; (c) the results of key milestone tests conducted prior to preparation of the report; (d) survivability; (e) suitability; (f) concept of operations, including basing considerations; (g) operations and maintenance support; (h) command and control considerations, including timelines for detection, decision-making, and engagement; (i) shortfall from intercepts; (j) force structure requirements; (k) effectiveness against countermeasures; (l) estimated cost of sustaining the system in the field; (m) reliability, availability, and maintainability; (n) geographic considerations, including limitations on the ability to deploy systems within operational range of potential targets; and (o) cost and cost-effectiveness, including total lifecycle cost estimates.
4. Scenarios to be assessed—the study should include an assessment of each system identified in paragraph (2) above regarding the performance and operational capabilities of the system to: (a) counter short-range, medium-range, and intermediate-range ballistic missile threats from rogue states to the deployed forces of the United States and its allies; and (b) defend the territory of the United States against limited ballistic missile attack.
5. Comparison with non-boost systems—the study should include an assessment of the performance and operational capabilities of non-boost missile defense systems to counter the scenarios identified in paragraph (4) above. (The results under this paragraph shall be compared to the results under paragraph (4) above.) For purposes of this paragraph, non-boost missile defense systems include: (a) Patriot PAC-3 System and the Medium Extended Air Defense System follow-on system; (b) Aegis Ballistic Missile Defense System, with all variants of the Standard Missile-3 interceptor; (c) Terminal High Altitude Area Defense System; and (d) Ground-Based Midcourse Defense System.

B

Biographies of Committee Members and Staff

L. David Montague (NAE) is an independent consultant and is retired president of the Missile Systems Division at Lockheed Martin Missiles and Space and a former officer of Lockheed Corporation. Mr. Montague has 50 years of experience in design, development, and program management of military weapon systems, particularly ballistic missiles, low-cost space launch vehicles, and ballistic missile defense systems. His experience includes the requirements, development, and policy issues of strategic forces and defense systems to protect against weapons of mass destruction. His expertise includes the definition, development, integration and management of strategic and tactical standoff strike weapon systems, exo- and endoatmospheric defenses for engaging these classes of threats, and the technologies and capabilities for guidance and control, surveillance and threat detection, cueing and targeting of these systems. Mr. Montague is a fellow of the American Institute of Aeronautics and Astronautics and received that Institute's Missile Systems Award in 1990. He has served on numerous scientific boards and advisory committees, to include task forces for both the U.S. Army and Defense Science Board and 8 years on the Navy Strategic Systems Steering Task Group. He was a member of the American Physical Society study panel on boost-phase intercept systems for national missile defense (published April 2003), served 3 years on the Los Alamos Laboratory Senior Advisory Group, and was a member of NASA's independent review group for constellation program management (2007). Mr. Montague is a former member of the NRC's Naval Studies Board and its Committee on Conventional Prompt Global Strike Capability. Mr. Montague received his bachelor of mechanical engineering and master of engineering equivalent from Cornell University in 1956.

Walter B. Slocombe is a partner at the law firm of Caplin & Drysdale and has served the U.S. government in numerous positions throughout his career. He served as Under Secretary of Defense for Policy from 1993 to 2000 and is former director of the DOD task force on Strategic Arms Limitation Talks (SALT). He has also served as senior advisor for national defense in the Coalition Provisional Authority for Iraq. In 2004, Mr. Slocombe was appointed by the President of the United States to the Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction. He is a member of the International Advisory Board of the Geneva Centre for the Democratic Control of Armed Forces and a former member of the Strategic Air Command Technical Advisory Committee. Mr. Slocombe served on the NRC's Committee on the Policy Consequences and Legal/Ethical Implications of Offensive Information Warfare and the Committee on Conventional Prompt Global Strike Capability.

David K. Barton (NAE) is an independent consultant. He received an A.B. in physics from Harvard College in 1949 and began his career as an engineering aid for the U.S. Army Signal Corps at White Sands Proving Grounds in 1946. He served as radar engineer at White Sands from 1949 to 1953 and at Signal Corps Engineering Laboratories at Fort Monmouth, New Jersey, until 1955. In 1955, Mr. Barton joined the RCA Missile and Surface Radar Department in Moorestown, New Jersey, as system engineer. He was awarded the RCA David W. Sarnoff Award for Outstanding Achievement in Engineering in 1958. In 1963, Mr. Barton became a consulting scientist to Raytheon Company at its Equipment Division in Wayland, Massachusetts, and later to its Missile Systems Division in Bedford. He was vice president for engineering at ANRO Engineering Inc. until 1984. Mr. Barton has served as member of the National Research Council's Air Force Studies Board, as chair of the Committee on the E-3A Radar, and as chair of the Committee on Advanced Airborne Surveillance Radar. He is a fellowof the Institute of Electrical and Electronics Engineers (IEEE) and received its Centennial Medal in 1984 and its Third Millennium Medal in 2000. He was named the IEEE Microwave Theory and Techniques Society Distinguished Microwave Lecturer in 1987-1988. His fields of research include radar systems, the propagation of radar waves, radar tracking and measurement, and radar guidance of missiles. He was a member of the American Physical Society study panel on boost-phase intercept systems for national missile defense. Mr. Barton serves on the NRC's Panel on Survivability and Lethality Analysis.

Melvin H. "Mel" Eisman is a senior cost analyst in the Management Science Department at the RAND Corporation. Prior to joining RAND in 1994, he worked at TRW Space and Defense Sector, Northrop Grumman Aircraft Division, Magnavox Advanced Products and Systems Company, General Dynamics, Naval Air Systems Command, and the Naval Aviation Logistics Center. At RAND, Mr. Eisman has generated system life-cycle cost estimates for analysis of alternative studies on future Air Force airborne tanker and electronic airborne attack options and participated in cost-effectiveness studies of (1) unmanned airborne systems platform/sensor force mix options for performing future Air Force missions, (2) countermeasures and other security initiatives for improving passenger security at rail stations and airports, (3) space-based and airborne intelligence, surveillance, and reconnaissance systems force mix options, (4) Air Force distributed small satellites over larger monolithic satellites, and (5) reusable launch vehicle options for supporting future Air Force space missions. In addition, he has recently been involved in assessing the utility of value models developed for DARPA's System F6 Fractionated Spacecraft Program within a DOD acquisition context; causal factors for improving military space acquisitions in delivering capabilities within cost and schedule; and performing independent program cost and risk assessments on one of JPL's upcoming Earth orbiting satellite missions. He is currently the RAND representative to the Air Force/NASA Space Systems Cost Analysis Group and a member of the American Institute of Aeronautics and Astronautics (AIAA). Mr. Eisman received an M.S. in industrial engineering from Pennsylvania State University.

David L. Fried has been an independent consultant since 1995. From 1993 to 1995 he was a professor of physics at the Naval Postgraduate School. Before that, from 1970 (when he founded the company) till 1993 (when he sold the company), Dr. Fried was the president of the Optical Sciences Company, and prior to that, from 1961 to 1970, he was employed by Rockwell International, where he held the position of manager in the Electro-Optical Laboratory of the Autonetics Division. Dr. Fried served for 20 years on the U.S. Army Science Board (ASB). For many years, he served on the ASB's standing committee on ballistic missile defense. In the 1960s, Dr. Fried published a series of papers on the optical effects of atmospheric turbulence that provided much of the analytic foundations for the development of adaptive optics systems and that resulted in the definition of the quantity now known as Fried's parameter. In 1981, Dr. Fried carried out the first analysis evaluating and establishing the feasibility of the use of atmospheric laser backscatter to control adaptive optics—a concept that now goes by the name of laser guide-star. He then designed, managed the development of the hardware for, and supervised an experiment that successfully demonstrated the validity of the laser guide-star concept. In 1993, he received the SPIE Technology Achievement Award for his initial laser guide-star work. In addition to his work related to optical propagation/turbulence effects/adaptive optics, Dr. Fried has done work in a variety of other electro-optics-related fields such as the suppression of infrared background clutter in moving target detection systems; analysis of laser speckle statistics; analysis of the effect of photo-detection-event driven shot noise on the precision of various types of optical measurements; the design and development of low-temperature-optics long-wavelength infrared sensors for use in midcourse ballistic missile defense; and in the design and performance analysis for space-based infrared sensors for missile and aircraft detection. He has also been involved in the search for a sound approach to the midcourse decoy discrimination problem for ballistic missile defense. Dr. Fried received a Ph.D. in physics from Rutgers University.

Alec D. Gallimore is Arthur F. Thurnau Professor of Aerospace Engineering at the University of Michigan, where he directs the Plasmadynamics and Electric Propulsion Laboratory. Professor Gallimore is also an associate dean at the Horace H. Rackham School of Graduate Studies, where he serves as the school's liaison to 25 graduate programs and departments in engineering, the physical sciences, and mathematics. Professor Gallimore is also on the faculty of the applied physics program at Michigan, is the director of the NASA-funded Michigan Space Grant Consortium, and is project director of the NSF-funded Michigan Alliances for Graduate Education and the Professorate. He received his Ph.D. in aerospace engineering from Princeton University. His primary research interests include electric propulsion, plasma diagnostics, space/reentry plasma simulation, use of plasma for energy production and environmental remediation, and nanoparticle physics. He has experience with a wide array of electric propulsion technologies including Hall thrusters, ion thrusters, arcjets, radio frequency plasma sources, 100-kilowatt-class steady magnetoplasmadynamic (MPD) thrusters, and megawatt-level quasi-steady MPD thrusters. Professor Gallimore has implemented a variety of probe, microwave, and optical/laser plasma diagnostics. He serves on the AIAA Electric Propulsion Technical Committee and is a fellow of AIAA. Professor Gallimore is an associate editor for the *Journal of Propulsion and Power* and for the *Joint Army Navy NASA Air Force Journal of Propulsion and Energetics* and has served on a number of advisory boards for NASA and DOD including the U.S. Air Force Scientific Advisor Board (AFSAB). He was awarded the Decoration for Meritorious Civilian Service in 2005 for his work on the AFSAB. He is co-founder of ElectroDynamic Applications, Inc. (EDA), a high-tech aerospace firm in Ann Arbor, Michigan, that specializes in plasma device engineering. Professor Gallimore has served on numerous NRC committees, including the Committee on Future Air Force Needs for Survivability and the Committee on Conventional Prompt Global Strike Capability.

Gen Eugene E. Habiger, U.S. Air Force (ret.), is distinguished fellow and policy advisor at the University of Georgia Center for International Trade and Security. General Habiger retired as a general, serving as the Commander-in-Chief, United States Strategic Command, where he was responsible for all U.S. Air Force and U.S. Navy strategic nuclear forces supporting the national security strategy of strategic deterrence. In this position, he established an unprecedented military-to-military relationship with his Russian counterparts, fostering extraordinary confidence building and openness. After his retirement from the U.S. Air Force General Habiger was appointed the U.S. Department of Energy's director of security and emergency operations. He serves as a distinguished fellow and policy adviser with the University of Georgia Center for International Trade and Security, where he assisted with the Center's international programs aimed at preventing weapons proliferation and reducing nuclear dangers. He has served as president and CEO of the San Antonio Water System and currently is on the Nuclear Threat Initiative's board of directors. He also serves as a senior fellow at the Gorbachev Foundation. General Habiger served on the NRC's Committee on Conventional Prompt Global Strike Capability.

Harvey L. Lynch recently retired after serving as an assistant director in the Particle Physics and Astrophysics directorate of the SLAC National Accelerator Laboratory (SLAC). He has over 40 years of experience in experimental high-energy particle physics (HEP). During that time he worked at laboratories in the United States, Germany, and Switzerland on experiments in the fundamental interactions of particles. One experiment resulted in the discovery of a new quark (charm), which launched a revolution in particle physics. He has been one of the leading members of the design team for three different HEP detectors, two at the SLAC in Menlo Park, California, and one at the Deutsches Elektronen Synchrotron in Hamburg, Germany. He was a deputy for detector technical liaison to the associate director for physics research at the superconducting supercollider (SSC) in Dallas, Texas. In that role he had the responsibility of technical oversight for the design of two very large HEP detectors planned for the SSC. His experience in arms control/defense-related work includes a leave of absence in 1986 spent at the Center for International Security and Arms Control at Stanford, when he prepared the report *Technical Evaluation of Offensive Uses of SDI,* which looked at the use of laser beams from space as weapons against ground or airborne targets. In 1989, he was part of the team from the U.S. Natural Resources Defense Council working with the Soviet Academy of Sciences for the joint "Black Sea Experiment" (on board a Soviet cruiser as part of a verification regime for submarine-launched cruise missile control by the passive detection of an onboard nuclear weapon by means of the radiation it emits. Most recently, he was a member of the American Physical Society team studying boost-phase missile interception.

Kenneth C. Malley, VADM, U.S. Navy (ret.), is currently an independent consultant. Admiral Malley retired from the Navy as a vice admiral after 37 years of service. He graduated from the U.S. Naval Academy in 1957 and served on destroyers in the Atlantic fleet until 1960, when he attended the U.S. Naval Postgraduate School, graduating in 1963 with an M.S.E.E. His first engineering duty assignment was as head of Navy Gun and Fire Control Systems and program manager for the Navy's first digital fire control system—the MK-86 GFCS. From 1967 to 1991 he served in various assignments in the Strategic Systems Program Office, becoming the director from 1985 to 1991. In his final assignment, Admiral Malley served as commander, Naval Sea Systems Command, with responsibility for all naval ships and weapons systems, except fleet ballistic missiles, and all shore activities, such as weapon laboratories and shipyards supporting the deployed systems. After retirement from the Navy in 1994, he held several vice presidential positions at ARINC, Inc., headquarters in Annapolis, Maryland, until 2002.

C. Wendell Mead is chief executive officer and chief technical director at AGRI, Inc., where he serves as a subject matter expert on ballistic missile defense and aerospace systems engineering, simulation, analysis, test, training and evaluation projects. He has broad experience in aerospace and missile system concept definition, simulation, analysis, engineering, integration, test, training, and evaluation; strategic analysis and defense policy formulation; cost analysis; logistics; and test range operations and maintenance. Previously, Mr. Mead held high level positions at SRS Technologies, U.S. Army Ballistic Missile Defense Advanced Technology Center, Lockheed Missiles and Space Company, and NASA Marshall Space Flight Center. Mr. Mead has M.S. degrees from Stanford University (management) and Auburn University (aerospace engineering).

Daniel L. Montgomery, BG, U.S. Army (ret.), is the CEO of Strategic Defense Solutions, a start-up founded in 2009 as a service-disabled, veteran-owned small business providing strategic and defense planning services. Prior to joining Strategic Defense Solutions, he served as director of Northrop Grumman's Air and Missile Defense market area. Retiring from the U.S. Army in 1999 with the rank of brigadier general, he ended a 32-yr military career with his last assignment as the senior acquisition executive for Air and Missile Defense Systems. General Montgomery held many senior management and leadership roles, including the U.S. Army's senior acquisition executive for air and missile defense systems. Today, General Montgomery serves as a member of the board of directors for the Chamber of Commerce of Huntsville/Madison County and as a member of the Association of the U.S. Army, the Navy League of the United States, the National Defense Industrial Association, and the Aerospace Industries Association. He has received many awards and decorations, including the Distinguished Service Medal, the Legion of Merit, the Bronze Star Medal, and the Meritorious Service Medal.

C. Kumar Patel (NAS/NAE) is a professor of physics and astronomy, chemistry, and electrical engineering at the University of California, Los Angeles (UCLA). He is also the founder and CEO of Pranalytica, Inc., a Santa Monica, California, company that carries out R&D and manufactures and sells trace gas sensors for in situ detection of chemical warfare agents and explosives, systems for standoff detection of explosives (IEDs), and high-power mid-wave infrared and long-wave infrared quantum cascade lasers for applications in defense, homeland security, and commercial systems. He served as vice chancellor for research at UCLA from 1993 to 1999. Prior to joining UCLA in March 1993, he was the executive director of the Research, Materials Science and Engineering and Academic Affairs Division at AT&T Bell Laboratories, Murray Hill, New Jersey. He joined Bell Laboratories in 1961, when he began his career by carrying out research in the field of gas lasers. He is the inventor of the carbon dioxide laser, which is one of the most widely used lasers in industry. Dr. Patel received his Ph.D. from Stanford University in 1961. In 1988 he was awarded an honorary doctor of science degree from the New Jersey Institute of Technology. In 1996 Dr. Patel was awarded the National Medal of Science by the President of the United States. Dr. Patel serves on the NRC's Committee on Developments in Detector Technology and its Panel on Sensors and Electron Devices.

Jonathan D. Pollack is a senior fellow with the John L. Thornton China Center at the Brookings Institution. Before that he was professor of Asian and Pacific studies and chairman of the Asia-Pacific Studies Group at the U.S. Naval War College. Between 2000 and 2004 he served as chairman of the College's Strategic Research Department. Prior to joining the War

College faculty in 2000, Dr. Pollack was affiliated with the RAND Corporation, where he served in a wide range of research and management positions. His major research interests include Chinese national security strategy; U.S. foreign and defense policy in Asia and the Pacific; Korean politics and foreign policy; and nuclear weapons and international politics. He is a member of the International Institute for Strategic Studies (IISS), the Council on Foreign Relations, the National Committee on U.S.-China Relations, and an emeritus member of the Committee on International Security and Arms Control, a standing committee of the National Academy of Sciences. He has authored numerous research monographs, edited volumes, journal articles, book chapters, and strategic commentaries, with particular emphasis on Chinese military development, U.S.-China relations, East Asian international relations, and U.S. defense strategy in East Asia. During 2008 and 2009 he undertook research on the rethinking of Korean nuclearization, supported by a grant from the John T. and Catherine D. MacArthur Foundation. A book based on this research, *No Exit: North Korea, Nuclear Weapons, and International Security*, was published by the IISS in 2010 in the Institute's new Adelphi Books series.

David M. Van Wie is chief technologist for precision engagement at the Johns Hopkins University Applied Physics Laboratory, where his principal research interests are in aerospace vehicle design and development with emphasis on propulsion systems and advanced aerodynamics for supersonic and hypersonic flight vehicles. Dr. Van Wie also holds appointments as research professor in the Department of Mechanical Engineering at Johns Hopkins University and lecturer in the Department of Aerospace Engineering at the University of Maryland. He received B.S., M.S., and Ph.D. degrees in aerospace engineering from the University of Maryland and an M.S. in electrical engineering, with emphasis on radar and communication systems, from Johns Hopkins University. Dr. Van Wie has served on numerous scientific boards and advisory committees, to include the NRC Committee on Conventional Prompt Global Strike Capability.

David R. Vaughan is a senior engineer in the Technology and Applied Science Department at the RAND Corporation. Prior to joining RAND in 1986, he worked at R&D Associates, the Institute for Defense Analyses, and the McDonnell Douglas Aerospace Corporation. At RAND, Dr. Vaughan has performed research on countering hostile UAVs, nontraditional ISR, and counterinsurgency aircraft. Previously, he supported studies on close air support: technology and tactics; space support for military operations; and intelligence, surveillance and reconnaissance end-to-end analysis. Earlier, he led projects on the reconnaissance and surveillance force mix, which analyzed airborne and space SIGINT, IMINT and MTI sensors and platforms; theater missile defense/critical mobile targets, which performed operational and technical analyses of boost- and ascent-phase intercept, and air-to-surface attack operations; advanced technical options for conventional cruise missiles; and a net assessment of U.S. and Soviet strategic missile penetration systems. At R&D Associates, he worked on U.S. and Soviet offense and defense systems. At the Institute for Defense Analyses, his work included surface-to-air interceptor missile performance limits, submarine-launched ballistic missile performance limits, and radar tracking and prediction analysis. He was a member of the American Physical Society study panel on boost-phase intercept systems for national missile defense and an ad hoc member of an Air Force Scientific Advisory Board on theater air and missile defense. He is an associate fellow of the AIAA and a recipient of the Leo Szilard Award of the American Physical Society. Dr. Vaughan received his Ph.D. in mechanical engineering from the Massachusetts Institute of Technology.

Dean Wilkening is at Lawrence Livermore National Laboratory, having recently moved from serving as a senior research scientist at the Center for International Security and Cooperation at Stanford University. He holds a Ph.D. in physics from Harvard University and worked at the RAND Corporation prior to coming to Stanford. His major research interests include nuclear strategy and policy, arms control, the proliferation of nuclear and biological weapons, bioterrorism, ballistic missile defense, and energy and security. His most recent research focuses on the technical, strategic, and political aspects of ballistic missile defense deployments in northeast Asia, south Asia, and Europe. Prior work focused on the technical feasibility of boost-phase ballistic missile defense interceptors. His recent work on bioterrorism focuses on understanding the scientific and technical uncertainties associated with predicting the outcome of hypothetical airborne biological attacks and the human effects of inhalation anthrax, with the aim of devising more effective civil defenses. He has participated in, and briefed, several National Academy of Science committees on biological terrorism and consults for several U.S. national laboratories and government agencies. Dr. Wilkening served on the NRC's Science and Technology for Countering Terrorism: Biological Panel.

Staff

Charles F. Draper is director of the National Research Council's Naval Studies Board (NSB). He joined the NSB in 1997 as Program Officer then Senior Program Officer and in 2003 became associate director and acting director of the NSB. During his tenure with the NSB, Dr. Draper has served as study director on a wide range of topics aimed at helping the Department of the Navy and DOD with their scientific, technical, and strategic planning. He served as study director for the report *Conventional Prompt Global Strike: Issues for 2008 and Beyond.* Before joining the NSB, Dr. Draper was the lead mechanical engineer at S.T. Research Corporation, where he provided technical and program management support for satellite Earth station and small satellite design. He received his Ph.D. in mechanical engineering from Vanderbilt University in 1995; his doctoral research was conducted at the Naval Research Laboratory (NRL), where he used an atomic-force microscope to measure the nanomechanical properties of thin-film materials. In parallel with his graduate student duties, Dr. Draper was a mechanical engineer with Geo-Centers, Inc., working on-site at NRL on the development of an underwater X-ray backscattering tomography system used for the nondestructive evaluation of U.S. Navy sonar domes on surface ships.

C

Summary of Meetings

January 13-15, 2010, in Washington, D.C. First committee meeting: briefings on congressional perspectives from the Senate Armed Services Committee; introduction to ballistic missile defense systems (BMDS) from the Missile Defense Agency (MDA); BMDS and early intercept overview, MDA; Department of Defense (DOD) perspectives, Office of the Deputy Assistant Secretary of Defense for Nuclear and Missile Defense Policy; Department of State perspectives, Deputy Assistant Secretary of State, verification compliance implementation; intelligence community perspectives, Office of the Director, National Intelligence; threat and geopolitical implications, MDA; early intercept considerations, MDA; phased adaptive approach, MDA; Aegis, MDA; kinetic energy interceptor (KEI), MDA; airborne laser, MDA; miscellaneous other boost-phase concepts, MDA; command and control, battle management, and communications, MDA.

February 16-19, 2010, in Washington, D.C. Second committee meeting: terminal high-altitude area defense (THAAD), MDA; Patriot advanced capability 3 (PAC-3), Army PEO Missiles and Space; Medium Extended Air Defense System (MEADS), Army PEO Missiles and Space; Aegis (more details), MDA and the Johns Hopkins University Applied Physics Laboratory; ground-based interceptor (GBI) system, MDA; non-Aegis radars, MDA.

March 16-19, 2010, in Washington, D.C.(at the National Academies and at MDA Headquarters). Third committee meeting: BMDS discrimination, MDA; threat information relevant to BMDS, MDA; radio frequency discrimination, MDA; BMDS interceptor discrimination and handover, MDA; airborne laser (ABL) system performance, MDA; KEI, MDA; optical signature and discrimination phenomenology, MDA; current concepts for space-based approaches to boost-phase/ascent-phase intercept, MDA; description of existing and planned boost-phase/early-intercept phase technology demonstration programs, MDA.

April 20-23, 2010, in Washington, D.C. Fourth committee meeting: space system architecture, MDA; operational and technical details of the space-based infrared system (SBIRS), SBIRS Program Office, Aerospace Corporation and Lockheed Martin; operational and technical details of forward-based X-band radars, MDA, Mitre Corporation, and Raytheon; operational and technical details of ground-based radars, MDA, MITRE Corporation, and Raytheon; operational and technical capabilities of the Clear, Thule, and Fylingdale radars; status and capabilities of the enhanced perimeter acquisition radar characterization system and PAVE phased-array warning system, MDA, MITRE Corporation, and Raytheon; operational and technical details of airborne sensors under consideration for supporting early intercept, Massachusetts Institute of Technology (MIT); current and emerging electro-optical sensor technologies, Utah State University, the Johns Hopkins University Applied Physics Laboratory, and the Aerospace Corporation; optical signature and discrimination phenomenology, MDA.

May 18-21, 2010, in Washington, D.C. Fifth committee meeting: policy considerations related to study terms of reference, including the Ballistic Missile Defense Review and the Nuclear Posture Review, Deputy Assistant Secretary of Defense, Nuclear and Missile Defense Policy, Office of the Secretary of Defense (OSD); acquisition and technical considerations related to study terms of reference, Deputy Director, Strategic Warfare, OSD for Acquisition, Technology, and Logistics; operational, policy, technical, and other considerations related to study terms of reference, director of the MDA; ballistic missile defense requirement and considerations related to study terms of reference, director, Joint Integrated Air and Missile Defense/Deputy Director for Force Protection, Joint Staff, J-8; perspectives on study terms of reference, NAS, NAE, and IOM members; perspectives on the study terms of reference, president of the Center for Security Policy, director of the Nuclear Strategy and Nonproliferation Initiative, the New America Foundation, MIT, Los Alamos National Laboratory, and the Union of Concerned Scientists; and threat description and projections, Office of the Director, National Intelligence.

June 15-17, 2010, at Redstone Arsenal, Huntsville, Alabama. Sixth committee meeting: Missile and Space Intelligence Center (MSIC) perspectives, technical director, MSIC; ground-based midcourse defense (GMD) perspectives, MDA and the Naval Surface Warfare Command; comprehensive discrimination briefings for early-intercept, ascent, and midcourse phases: threat identification toolbox, MDA and MIT; comprehensive discrimination briefings for early-intercept, ascent, and midcourse phases: field observations of ballistic missile threats, MDA and MIT; comprehensive discrimination briefings for early-intercept, ascent, and midcourse phases: AN/TPY-2 and SBX radar discrimination, MDA and MIT; comprehensive discrimination briefings for early-intercept, ascent, and midcourse phases: radar measurements of debris and clutter, MDA and MIT; comprehensive discrimination briefings for early-intercept, ascent, and midcourse phases: ground-based midcourse (GM) flight test data, MDA and Boeing; comprehensive discrimination briefings for early-intercept, ascent, and midcourse phases: Aegis BMD and MDA; comprehensive discrimination briefings for early-intercept, ascent, and midcourse phases: critical measurements flight test program, MDA and MIT; comprehensive discrimination briefings for early-intercept, ascent, and midcourse phases: midcourse space experiment EO/IR data exploitation, MDA and MIT; GMD perspectives, MDA, Boeing, Northrup Grumman, and Raytheon; Iran scenario, MDA; Israeli perspectives, consultant; THAAD perspectives, Lockheed; PAC-3 perspectives, MDA.

June 23, 2010, at Lockheed Martin, Sunnyvale, California. Seventh meeting (subcommittee meeting perspectives from Lockheed Martin on boost-phase missile defense systems and Lockheed Martin’s assessment of performance and operational capabilities, Lockheed Martin.

July 13-16, 2010, in Washington, D.C. Eighth committee meeting: contractor perspectives, Northrop Grumman, Boeing, Lockheed Martin, Raytheon, Lawrence Livermore National Laboratory, and Alliant Tech Systems; Air Force/MDA Operational Feasibility Study on Air-Launched Hit-to-Kill, Headquarters, USAF (A5XS) and MDA.

August 17-18, at Fort Greely, Alaska, and at Colorado Springs, Colorado. Ninth committee meeting: briefing by MDA and Alaska 49th Missile Defense Battalion (GMD-BN); distributed multiechelon training system (DMETS), NORTHCOM J31; SIV/SILO visit, NORTHCOM J31; missile field tour, NORTHCOM J31; missile defense element, NORTHCOM J31; DMETS run and discussion, NORTHCOM J31; Two-command brief, North American Aerospace Defense Command (NORAD) and NORTHCOM; commander, NORAD and NORTHCOM brief; ballistic missile defense intelligence update and discussion, NORTHCOM J31; observation of Night Blue exercise, NORTHCOM J31.

September 12-17, 2010, at Woods Hole, Massachusetts. Tenth committee meeting: writing meeting, full committee.

October 19-22, 2010, in Washington, D.C. Eleventh committee meeting: writing meeting, entire committee.

November 8-12, 2010, at NAS Beckman Center, Irvine, California. Twelfth committee meeting: writing meeting, full committee.

January 18-21, 2011, at Washington, D.C. Thirteenth committee meeting: writing meeting, full committee.

February 14-18, 2011, at Washington, D.C. Fourteenth committee meeting: writing meeting, partial committee

March 7-11, 2011, at RAND Corporation, Santa Monica, Californina. Fifteenth committee meeting: writing meeting, partial committee.

March 20-25, 2011, at NAS Beckman Center, Irvine, California. Sixteenth committee meeting: writing meeting, full committee.

May 16-20, 2011 at Washington, D.C., and at RAND Corporation, Santa Monica, California. Seventeenth committee meeting: writing session, partial committee at East and West Coast sites.

July 27-29, 2011 at Washington, D.C. Eighteenth committee meeting: response-to-review session, partial committee.

D

Acronyms and Abbreviations

AAW	antiaircraft warfare
ABI	airborne-based interceptor
ABIR	airborne infrared
ABL	Airborne Laser
ABM	antiballistic missile
ABMDA	Advanced Ballistic Missile Defense Agency
ABT	air-breathing threat
ACS	attitude control system
ADSAM	air-directed surface-to-air missile
AEU	antenna equipment unit
AHTK	airborne hit to kill
ALCM	air-launched cruise missile
ALHK	air-launched hit-to-kill
ALTB	airborne laser test bed
AMaRVe	advanced maneuvering reentry vehicle
AMD	air and missile defense
AMRAAM	advanced medium-range air-to-air missile
AMTI	air moving target indication
AN/TPY	Army Navy/transportable radar surveillance
AO	adaptive optics
AoA	analysis of alternatives
AOR	area of responsibility
APS	American Physical Society
ASALM	advanced strategic air-launched cruise missile
ASAT	antisatellite
ASCM	antiship cruise missile
ASCMD	antiship cruise missile defense
ASUW	antisurface warfare
ASW	antisubmarine warfare
ATDLS	advanced tactical data link system
AT&L	Acqusition, Technology and Logistics
ATR	automatic target recognition
AUPC	average unit production cost
AWACS	airborne warning and control system
AWS	Aegis weapon system
BAMBI	ballistic missile boost intercept
BAT	BMC4I advanced technology
BDA	battle damage assessment

BILL	beacon illuminator laser
BMC2	battle management command and control
BMC3	battle management command, control, and communications
BMC4I	battle management command, control, communications, computing, and intelligence
BMD	ballistic missile defense
BMDO	Ballistic Missile Defense Office
BPI	boost-phase intercept
C2	command and control
C2BMC	command and control battle management center
C3	command, control, and communications
C3I	command, control, communications, and intelligence
C4ISR	command, control, communications, computing, intelligence, surveillance, and reconnaissance
CALCM	conventional air-launched cruise missile
CAP	combat air patrol
CBO	Congressional Budget Office
CC&D	camououflage, concealment, and deception
CC&D	common command and decision (Navy)
C&D	command and decision
CE	combat enhancement
CEC	cooperative engagement capability
CEP	cooperative engagement processor
CEP	circular error probable
CEU	cooling equipment unit
CID	combat identification
CINC	commander in chief
CIWS	close-in weapon system
CMD	cruise missile defense
CME	Caribou, Maine
COCOM	combatant commander
COIL	chemical oxygen-iodine laser
CONOPS	concept of operations
CONUS	continental United States
COTS	commercial off-the-shelf
CRD	capstone requirements document
CSS-5	medium-range, road-mobile, solid-propellant ballistic missile (China)
CSV	cable support vehicle
DACS	divert and attitude control system
DARPA	Defense Advanced Research Projects Agency
DASO	demonstration and shakedown (missile)
DEM/VAL	demonstration and validation
DISA	Defense Information System Agency
DOD	Department of Defense

DOE	Department of Energy
DOF	degrees of freedom
DOT	Department of Transportation
DSP	Defense Support Program
DTRM	dual-thrust rocket motor
E2	enhanced effectiveness
EAM	emergency action message
ECS	engagement control station
EEU	electronic equipment unit
EI	early intercept
EIT	exoatmospheric interceptor technology
EKV	exoatmospheric kill vehicle
EMD	engineering and manufacturing development
EMP	electromagnetic pulse
EO	electro-optics
EOC	early operational capability
EOR	engage on remote
EPP	electronic power plant
ERINT	extended-range interceptor
ERIS	exoatmospheric reentry interceptor system
ESM	electronic support measure
EW	electronic warfare
EWS	early warning system
FAIR	flying along infrared
FBM	fleet ballistic missile
FBX	X-band radar (standalone version)
FEWS	future early warning system
FGA	Fort Greely, Alaska
FLIR	forward-looking infrared
FOC	final operational capability
FU	fire unit
FY	fiscal year
FYDP	future years defense plan
GBI	ground-based interceptor
GBR	ground-based radar
GBX	ground-based X-band radar
GEM	general energy management
GEO	geosynchronous orbit
GMD	Ground-Based Midcourse Defense
GMD-E	Ground-Based Midcourse Defense-Evolved
GMTI	ground moving target indication
GN&C	guidance, navigation, and control
GPS	Global Positioning System

HALO-2	High Altitude Observatory 2 (program)
HEL	high-energy laser
HF/DF	hydrogen fluoride/deuterium fluoride
HOE	homing overlay experiment
HPI	high-performance interceptor
HTK	hit to kill
HTPB	hydroxyl terminated polybutadiene
I&T	interceptor integration and testing
IBCS	integrated battle command system
ICBM	intercontinental ballistic missile
ICD	initial capabilities document
IDT	IFICS data terminal
IFICS	in-flight interceptor communications station
IFTU	in-flight target update
IMINT	imagery intelligence
IMU	inertial measurement unit
INS	inertial navigation system
IOC	initial operational capability
IOT&E	initial operational test and evaluation
IP	Internet Protocol
IR	infrared
IRBM	intermediate-range ballistic missile
ISR	intelligence, surveillance, and reconnaissance
ITOF	interceptor total time of flight
JTO	Joint Technology Office
KEI	kinetic energy interceptor
KEP	kinetic energy projectile
KEW	kinetic-energy vehicle
KKV	kinetic-kill vehicle
KV	kill vehicle
LADAR	laser detection and ranging (laser radar)
LAN	local area network
LCC	life-cycle cost
LCS	launch control system
LIDAR	laser identification and ranging
LOR	launch on remote
LOS	line of sight
LRIP	low rate initial production
LSI	lead system integrator
LSRBM	long- and short-range ballistic missiles
LWIR	long-wave infrared
MARB	maneuverable reentry body

MaRV	maneuverable reentry vehicle
MCS	mission control system
MDAP	major defense acquisition program
MDA	Missile Defense Agency
MDIOC	Missile Defense Integrated Operations Center
MEADS	Medium Extended Air Defense System
MILCON	military construction
MKV	multiple kill vehicle
MLRB	medium-lift reentry body
MRBM	medium-range ballistic missile
MSE	missile segment enhancement (improved PAC-3)
MSX	midcourse space experiment
MTCR	missile technology control regime
MTS-B	multispectral targeting system, version B
MWIR	midwavelength infrared
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NCA	National Command Authority
NCADE	network-centric airborne defense element
NGA	National Geospatial-Intelligence Agency
NGAM	next-generation Aegis missile
NMD	national missile defense
NRC	National Research Council
NRO	National Reconnaissance Office
O&S	operations and support
O&S sunk	operations and support (expended)
OC	operations central
OCM	overland cruise missile
OCMD	overland cruise missile defense
OIF	Operation Iraqi Freedom
OPEVAL	operational evaluation
ORD	operational requirements document
OSD	Office of Secretary of Defense
PAA	phased adaptive approach
PAC-3	Patriot advanced capability 3
PB	President’s budget
PBDI	postboost, predeployment intercept
PG	precision-guided
PGM	precision-guided munition
PPLI	precision position location information
PPU	prime power unit
PTSS	Precision Tracking and Surveillance System

QDR	Quadrennial Defense Review
QOS	quality of service
RB	reentry body
R&D	research and development
RCS	radar cross section
RDT&E	research, development, testing, and evaluation
RF	radio frequency
RIM-66C	ship-launched medium-range, surface-to-air missile (Navy) (first version of SM-2)
ROE	rules of engagement
ROK	Republic of Korea
ROM	rough order of magnitude
RS	radar set
RV	reentry vehicle
S&T	science and technology
SAFB	Schriever Air Force Base, Colorado
SAM	surface-to-air missile
SAR	synthetic aperture radar
SBI	space-based interceptor
SBX	sea-based X-band radar
SBIRS	spaced-based infrared aystem
SDACS	solid divert and atitude control system
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SECDEF	Secretary of Defense
SEP	spherical error probable
SES	shoot-engage-shoot
SFS	shoot-fail-shoot
SIAP	single integrated air picture
SIGINT	signal intelligence
SIOP	single integrated operational picture
SLBM	submarine-launched ballistic missile
SLS	shoot-look-shoot
SLV	space launch vehicle
SM	standard missile
SM-3	Standard Missile-3
SMRBM	short- and medium-range ballistic missiles
SOF	Special Operations Forces
SORT	Strategic Offensive Reductions Treaty
SPY-1	naval phased-array radar
SRBM	short-range ballistic missile
SSP	Strategic Systems Programs
STAP	space-time adaptive processing
START	Strategic Arms Reduction Treaty

STRATCOM	U.S. Strategic Command
STSS	Space Tracking and Surveillance System
SV	support vehicle
T2	go-time to go
TAD	theater air defense
TADIL	tactical digital information link
TAMD	theater air and missile defense
TBM	theater ballistic missile
TBMD	theater ballistic missile defense
TCS	theater combat system
TD-2	Taepo'o-dong-2 missile (North Korea)
TDACS	Throttleable Divert and Attitude Control System
TEL	transporter erector launcher
TFCC	THAAD fire control and communications
THAAD	Terminal (formerly theater) High-Altitude Area Defense
THEL	tactical high-energy laser
TILL	tracking illuminator laser
TLE	target location error
TMD	theater missile defense
TOC	tactical operations center
TOM	target object map
TOS	tactical operations station
TPS	thermal protection system
TPY-2	forward-based X-band radar
T/R	transmit/receive
TRL	technology readiness level
TSC	theater surface combatant
TSG	tactical support group
TSRM	third-stage rocket motor
TT&C	tracking, telemetry, and communications
TTPs	tactics, techniques, and procedures
TVM	target via the missile
TWAA	tactical warning and attack assessment
UAV	unmanned aerial vehicle
UEWR	upgraded early warning radar
UHF	ultrahigh frequency
USA	United States Army
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy
VAFB	Vandenberg Air Force Base, California
V_{bo}	Burnout velocity
VLS	vertical launch system

VSR	volume search radar
WMD	weapons of mass destruction
XBR	X-band radar

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System Cost Methodology

SCOPE OF LIFE CYCLE ESTIMATES

Life cycle costs (LCC) for each of the existing and proposed space-based early warning IR systems, ground- and sea-based radar systems, and defensive layers of intercept systems are defined as consisting of development, production, and sustainment costs with the last named over a 20-yr period. For the purposes of this study, LCC is divided into these three categories to allow assessing the relative costs across the mix of interceptor and sensor system options for improving missile defense.

Development costs are the cost of engineering activities needed to design and develop baseline and block upgrades of interceptor boosters, kill vehicles (KVs), early warning sensor and radar systems, and other supporting components and infrastructure, with Missile Defense Agency (MDA) annual budget requests for funds reported as research, development, test, and evaluation (RDT&E) appropriations consistent with the military services.[1]

Procurement costs for the manufacture of missile interceptor KVs, early warning sensor and radar systems, and associated equipment, including, as needed, the purchasing of Aegis-class ships. Construction costs are included as part of procurement and defined as those activities required to build the physical infrastructure, including power generators and maintenance facilities, that supports a given missile defense system or ship-based radar system. Procurement cost also includes the costs of integrating the applicable systems noted above into the existing infrastructure.[2] In addition, the procurement cost of interceptors includes the production of the total quantity committed for the inventory to achieve full operational capability (FOC).

Sustainment costs are the costs of the routine efforts to operate and maintain the system over a nominal 20-yr lifetime. Depending on the expected service life of the assets, sustainment costs can include the modification, upgrades, and/or replacement costs of procuring new systems as needed.

Following development and during the sustainment phase and for the purposes of maintaining the necessary operational proficiency, readiness, and training; sustainment costs include costs for conducting engagement exercises and missile tests, which in turn include the costs of procuring test interceptors, target missiles, parts, and so on; and the sustaining engineering costs for performing the tests, assessing the missile's performance, diagnosing

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[1] The breakout and definition of the three categories of cost, especially as they relate to the life cycle cost of ballistic missile interceptors are consistent with recent Congressional Budget Office (CBO) reports on missile defense.

[2] To account for this cost for ground-based interceptor systems similar to the ground-based missile defense (GMD) boost-phase intercept (BPI) systems, the committee applied a factor of 40 percent to account for costs of integrating the interceptor system and subsystems into the existing infrastructure. The integration activities are assumed to include assembly, installation, and integration at the ground-based interceptor launch site comparable to the silos and other infrastructure and the missile fields at Fort Greely, Alaska (FGA). This factor of 40 percent agrees with previous CBO reports on missile defense.

potential success and root causes of failure events as part of the overall integrated system test plans toward achieving the system's overall operational readiness and training required.[3]

RELATIONSHIP OF LIFE CYCLE COST ESTIMATES TO MDA BUDGET

For the purposes of this study, LCC are separated into development, production, and sustainment costs to enable assessing relative costs across system options for improving missile defense. It should be pointed out that through the DOD FY 2011 President's Budget (PB), submitted to Congress in February 2010, funding for MDA included funding for production (manufacturing) and sustainment operations, all under the single budget category of RDT&E. However, MDA's most recent budget justification materials for the FY 2012 PB submitted to Congress in February 2011, separated out what were formerly RDT&E program funds into procurement, military construction (MILCON), and the operations and maintenance (O&M) program element funds.

The basis for estimates of 20-yr sustainment costs for the MDA systems and the associated funds required will consist of both MDA RDT&E (procurement-related) budgets and the military service's O&M and military personnel (MILPERS) funds, with specific sustainment responsibilities identified in system-unique memoranda of agreement (MOAs). As stated by LTG Patrick J. O'Reilly, USA, Director, Missile Defense Agency, defines operations and support (O&S) responsibilities including in the majority of cases MDA's role in the material sustainment and funds for procuring replacement spares and the implementation of P3I modifications of fielded systems. Breakout of sustainment costs includes training costs, routine maintenance costs, operational tests, and ongoing operational integration.

"Should" vs. "Will" Cost Guidance for Bounding the Range Estimates

Consistent with the Memorandum for Secretaries of the Military Departments and Directors of the Defense Agencies issued on November 3, 2010, and effective November 15, 2010, the committee made a concerted effort to incorporate the guidance on developing "should cost" targets as one of its "sound" estimating techniques.[4]

The committee generated 20-yr LCC range estimates for each of the committee's recommended systems and those recently initiated by MDA systems based on first assessing the current technical and manufacturing maturity of all the systems and then generating "should" cost estimates as the lower bound (or minimum) costs based on the following:

- Scrutinizing every element of program cost,
- Assessing whether each element can be reduced by, for example, challenging the learning curves of similar systems, and

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[3] Consistent with previous CBO reports, the committee assumed that the additional number of test interceptors that need to be procured is based one test conducted every 2 years over the 20-yr lifetime of the system. The test plan is assumed to have two purposes: (1) testing out the performance of the current system baseline design of the interceptors, which includes any improvements to the booster stages as well as to the KV propulsion and IR seeker or divert systems and (2), from an event-driven perspective for demonstrating the capability of intercepting target missiles in scenarios mirroring threats from potential adversaries.

[4] The OSD policy on this subject is based on the guidance described in the "Drive Productivity Growth Through Will Cost/Should Cost Management" article, issued by the Defense Acquisition University (DAU) Acquisition Community Connection.

- Applying other recently implemented or proposed industry productivity improvements as part of reducing the total costs of doing business with the government, including, for example by reducing overhead rates, indirect costs, and other contractor cost-cutting measures.

The OSD policy states that the metric of success for "should cost" management is leading to annual productivity increases of a few percent from all ongoing contracted activities as program managers execute at lower cost than budgeted. OSD policy guidance believes industry can succeed in this environment because OSD and the military services will tie better system performance to higher corporate profits and because affordable programs will be less likely to face cancellation.

This is in contrast with system costs based a program's "will" cost, on which the committee bases its upper bound, or maximum, estimates. These estimates are focused on business-as-usual costs similar to comparable programs in the past where the requested annual budget was fully obligated and expended over time. The higher "will" cost estimate is also used as the basis of the independent cost estimate (ICE) performed by the OSD Cost Assessment and Policy Evaluation (CAPE) office for establishing program budgets that support major acquisition milestone reviews. As mentioned, the committee based these maximum cost targets on analogous systems and program expenditures over comparable acquisition phases where reasonable efficiency- and productivity-enhancing efforts were undertaken. This approach to estimating a system's "will" upper bound cost targets is consistent with and similar to the CAPE ICE estimating methods and program budget results expected for all ACAT I programs as they advance through the major milestones of the acquisition process.

Observations on System "Should Cost" Comparisons

In looking at previously stated $71 million to $85 million average unit procurement cost for the current and projected ground-based interceptor all up round, the committee wondered how that cost compared with the cost for other weapons of comparable capabilities and complexity. It extracted costs and quantities from DOD Selected Acquisition Reports (SARs) for several programs that allowed it to compare RDT& E efforts and early unit all up missile round costs.

Several of the U.S. Navy's Trident program SARs provided interesting data. The committee believes the Trident II D-5 and GBI all up rounds are of equal complexity except for the flight tests, which are not separately identified in either RDT&E cost. Table E-1 compares

TABLE E-1 Comparison of GMI and Trident II Missiles

	GMD Interceptor System	Trident II (D-5) Missiles
RDT&E time frame	1998 to 2009[a]	1978 to 1993[b]
Interceptor AUPC (million $)	71-84[c]	54[d]
Production lot quantity	52	54

[a] The GMD program started with NMD DEM/VAL for the BPI followed by GMD block development.

[b] The Trident II program includes 3 years of concept definition, 3 years of advanced development, and 10 years of full-scale development (FSD).

[c] MDA provided the committee with this estimate.

[d] The Trident II D-5 missile AUPC cost estimates were the most recent Program Manager's estimates to completion (ETC) for the first weapons procurement production contracts awarded after FSD to Lockheed-Martin in March 1984 for missiles and to Hughes Aircraft in July 1989 for the electronics packages as reported in "TRIDENT II (D-5) SAR," December 31, 1990. The AUPC also includes the Program Manager's ETC for the Kearfott Guidance contract awarded in October 1989 for guidance packages as reported in that same document.

the RDT&E time frame for the GMD interceptor system, its average unit procurement cost (AUPC) in FY 2010 constant dollars, and production lot quantity like those of the Trident II D-5 missiles.

The Trident II AUPC is for an all-up round for the post-boost vehicles, stellar inertial guidance, and test instrumentation for a first production lot quantity of 54 missiles built immediately after FSD. The AUPC range estimate for GBIs for a total quantity of 52 missiles, of which 30 interceptor have already been fielded and produced, 20 with the original Capability Enhancement I (CE-I) KV and 10 with the Capability Enhancement II (CE-II) EKV. The remaining 22 missiles are currently being funded through FY 2016.

The lower bound, or minimum AUPC estimate for producing 52 three-stage GBIs at $71 million (based on continued funding through FY 2016) is 32 percent higher than the comparable average unit cost of 54 Trident II D-5 missiles (without the warheads) at $54 million (both in constant FY 2010 dollars).

ASSESSMENT OF MDA ONGOING PROGRAM BUDGETS AND SOURCES OF DISCRETIONARY FUNDS

Before describing the databases, ground rules and assumptions, and cost methods used for generating system LCC, the effects of the committee's proposed recommendations on affordability concerns and the MDA current and projected annual budget ceilings through the Future Years Defense Plan (FYDP), on the current MDA ongoing budget commitments of all the programs of record, and on the level of discretionary funds available that could potentially be redirected to implement changes as early as FY 2012 and the out-years.

Figure E-1 below provides a top-down breakout of the FY 2011 MDA budget for each of the three major system acquisition phases and costs associated with LCC. The budget for testing is separated from that for sustainment to allow comparisons with the investment budget earmarked for development for procurement acquisition phases.

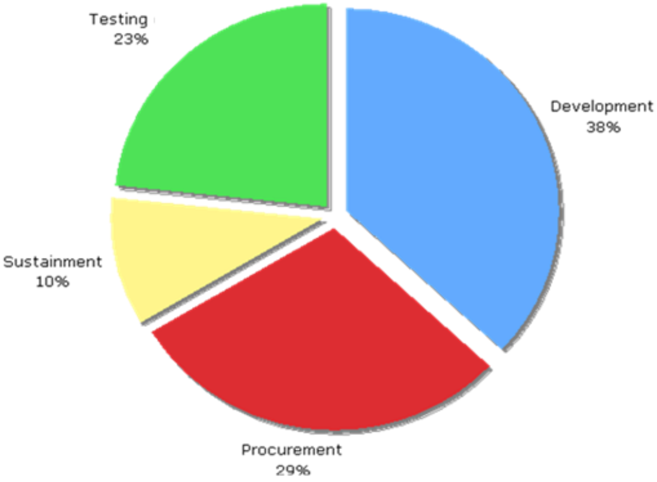


FIGURE E-1 MDA budget breakout by LCC phases. The total portfolio investment budget depicted in this figure does not include $431 million for RDT&E funds for Pentagon Reserve and MDA management headquarters nor does it include the MILCON budget or BRAC funds. The testing budget includes funds for Joint Warfighter exercises and war games but does not include funds for modeling and simulation, which were considered to be part of the development phase.

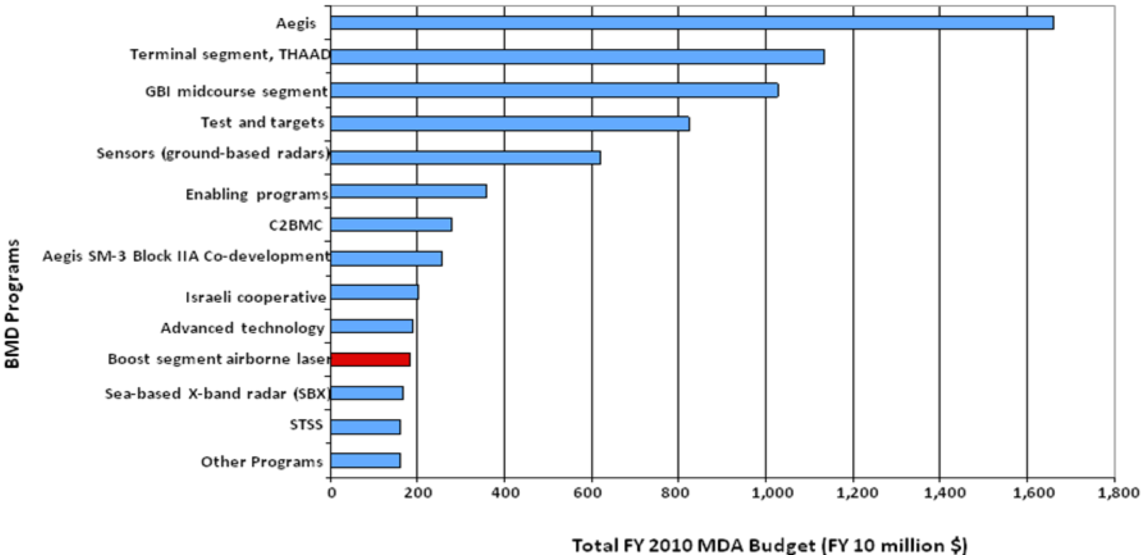
Table E-2 below provides further breakdown of programs considered as part of development from highest to lowest by percent of the $2.9 billion of FY 2011 funds for MDA programs of record beginning with the Aegis and ending with PTSS. Table E-2 reflects a change from the programs funded in FY 2010.

TABLE E-2 MDA FY-2011 Major Development Programs of Record

Ballistic Missile Defense (BMD) Programs	Breakdown of Funding of Programs (%)[a]
Aegis	29
BMD enabling programs	14
Aegis SM-3 Block IIA codevelopment	11
Aegis ashore (SM-3 Block IIB)	9
C2BMC	9
GMD midcourse segment	6
Advanced technology	4
Airborne infrared	4
Directed energy research	3
Ground-based radars	3
Terminal segment of THAAD	3
Precision tracking and surveillance system (PTSS)	3
Other	2

NOTE: C2BMC, command and control battle management center; THAAD, Terminal High-Altitude Area Defense.
[a] Portion of $2.9 billion FY 2010 funds for development.

Figure E-2 displays the magnitude of the budget changes contained in the FY 2011 MDA President's Budget (PB) submitted in February 2010. On the top bar chart, the boost segment airborne laser program has been terminated (denoted by the red bar). Beginning with the FY 2011 budget, the bottom bar chart (see the green bar), along three other new programs added in the FY 2011 budget: the land-based SM-3 interceptor, ABIR, and PTSS programs.



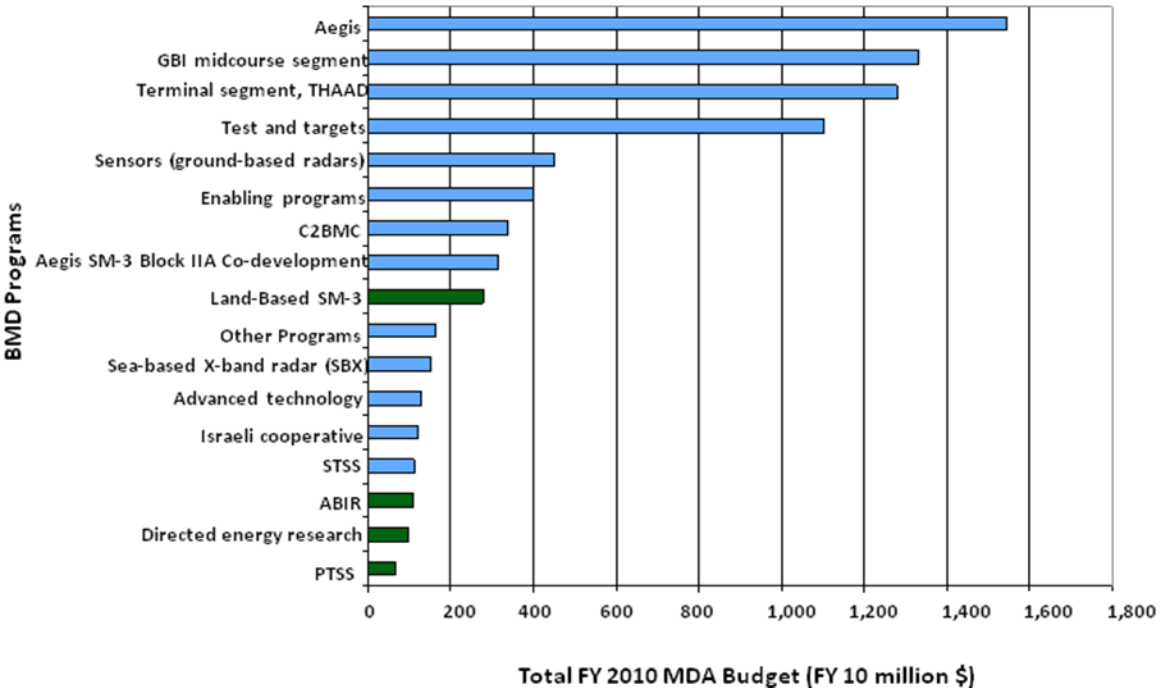


FIGURE E-2 MDA program budget changes from FY 2010 to FY 2011. GBI, ground-based interceptor; STSS, space tracking and surveillance system.

Advanced Technology Programs

Of the 13 programs Table E-2 (top), at least three advanced technology programs may be considered part of what is being defined as MDA's discretionary budget, where the investment does not appear to directly lead to a system procurement phase without first having to undergo a next-step system development activity proposed by MDA and funded within the FYDP or in the next 5-yr time frame. These three programs—BMD Enabling, Advanced Technology, and Directed-Energy Research—comprise 21 percent, or approximately $600 million, of the total development funds of $2.9 billion (in FY 2010 dollars).

Approximately 14 percent of the funds are for BMD Enabling programs, which are focused on developing critical processes needed to integrate stand-alone missile defense systems into a layered BMD system to achieve cost and operational efficiencies by improving protection performance within increased defended areas and minimizing force structure costs.

Another 4 percent of MDA's development budget is allocated for advanced technology efforts as a hedge against future threat uncertainties focused on funding next-generation and game-changing technologies with promising operationally cost-effective capabilities and developing and demonstrating the maturity of relevant components for future BMDS architectures.

A third development program, directed energy research, consuming 3 percent of the total MDA development budget, is focused in the near-term on the following:

- Using an aircraft test platform in flight, along with ground tests, to characterize high-energy laser beam propagation and the effects of atmospheric (1) propagation and (2) boundary layer and jitter with varying engagement geometries,

- Developing and experimenting with diode-pumped gas lasers, fiber lasers, solid-state and advanced high-power laser optics,
- Investigating lethality, counter-countermeasures, beam propagation, modeling, laser beam combining, and additional innovative areas, and
- Analyzing alternatives to select out-year laser investments.

Shifting MDA Budget Trends

In addition to advanced technology funds being a potential source of future discretionary budget, the MDA continuing role in procurement of Aegis systems and material sustainment of deployed THAAD systems in FY 2012 and the out-years, has shifted and reduced the percent of total MDA funds earmarked from 38 percent in FY 2011 to 30 percent (proposed) in FY 2012. As displayed in Figure E-3, FY 2012 procurement funding as a portion of the total MDA budget is10 percent higher than in FY 2011 owing primarily to a 7.5-fold increase in the Aegis FY 2011 program budget. The FY 2012 sustainment portion of the total MDA budget is 2 percent greater than the FY 2011 budget owing primarily to an increase in THAAD total sustainment funds, which now list a separate O&M budget line item for this system.

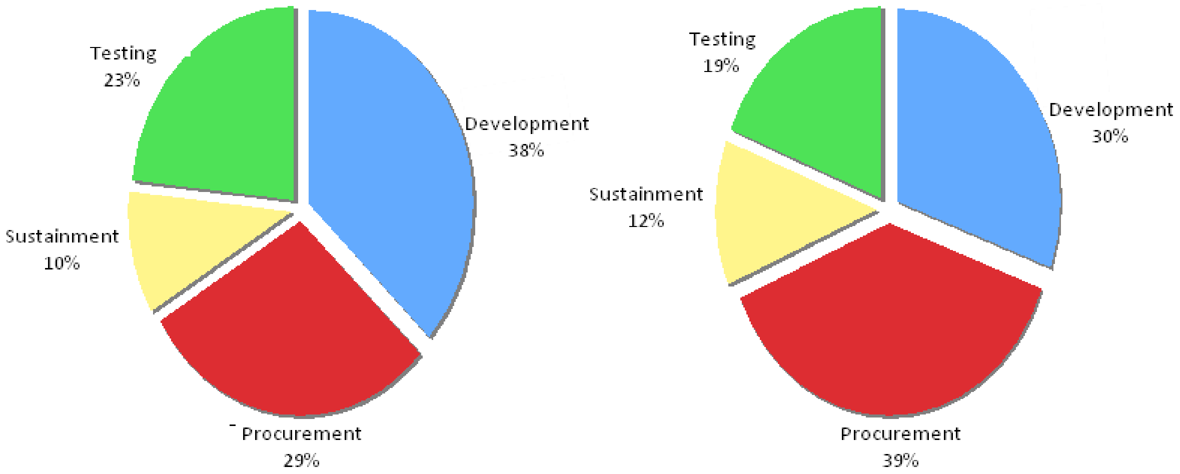


FIGURE E-3 Trends in MDA investment budget portfolio (FY2011 left pie chart; FY 2012 right pie chart).

MAJOR ESTIMATING GROUND RULES AND ASSUMPTIONS

All costs in this appendix are expressed as FY 2010 dollars[5].

The system LCC for each of the options considered will be displayed as “minimum” (or

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[5] Costs were escalated to FY 2010 dollars using inflation rates listed in the Air Force Raw Inflation Indices Base Year (FY) 2010 table by appropriation budget categories (e.g., Total Military Compensation (3500), Operations and Maintenance (3400), RDT&E (3600), MILCON (3300), Aircraft and Missile Procurement (3010/20), Other Procurement (3080), and Fuel. The inflation rates are based on OSD Raw Inflation Rates from December 11, 2009 and were issued by the Secretary of the Air Force/FMCEE as the OPR on January 8, 2010.

low) and "maximum" (or high) range estimates. For purposes of this study, the resulting LCC estimates for the minimum or the lower bound of the range estimates represent the projected "should cost" estimates[6] are computed based primarily on the data sources and cost estimating methods described later in this appendix.

Since the system options for improving U.S. missile defense range from new, advanced technology, long-range alternatives to near-term, well-proven technology alternatives, the system cost uncertainty of proposed programs and maximum, or upper bound, cost (system "will" cost) estimates must, from a budgetary perspective, include the potential for "representative" cost growth comparable to that of interceptors, early warning IR sensor systems, and ship and ground-based radar systems. In addition, maximum cost "estimates for systems that are defined only conceptually or that depend on the development of new technologies [could grow faster than those] for well-defined programs [that are] based on proven technologies."[7] For example, as reported by CBO and assessed by the RAND Corporation, the total development and procurement cost growth for missiles averaged 43.9 percent for six programs. Development cost growth was reported to 40.6 percent with procurement at 58.5 percent.[8]

DOD budgets for many past and current programs of record where in particular MDA and military service funds, have already been committed as part of the FY 2011 PB submitted in February 2010 and were waiting for approval in FY 2011. In addition, the PB budget justification for the majority of RDT&E and procurement program budgets contains annual projections in the FYDP through FY 2015.

For the purposes of this study and as a ground rule for estimating the cost of potential system options for improving U.S. missile defense, there is a set of system architecture baseline systems and programs of record that are operational and undergoing testing and demonstration, already fielded, or close to providing initial operational capability (IOC) before the end of the FY 2011 FYDP in FY 2015. Since the past annual funds through the approval of FY 2011 budget have already been expended or soon committed for these programs of record, the committee considered this portion of the LCC of the following systems as sunk cost and did not include them in their estimates.

KEY BALLISTIC MISSILE BENCHMARK DATA SOURCES

To the greatest extent possible and where the systems were technically similar to previous systems, development and production cost estimates were based on adjusting analogous costs from data from (1) historical programs of record supplied by MDA, (2) detailed breakout of

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[6] The "should" cost" and the "will" cost estimates are terms commonly used by the OSD CAPE office. "Should" cost estimates are most likely generated by program offices and will include additional contingency costs to account for the inherent uncertainty in the cost-estimating methods used and for mitigating known system-specific risks (e.g., requirements creep, program budget changes, and schedule slips).

[7] Congressional Budget Office. 2004. *Alternatives for Boost-Phase Missile Defense*, Washington, D.C., July.

[8] For most components, the cost-risk factors that CBO used were developed by the RAND Corporation and were based on published updates reported in Joseph G. Bolten, Robert S. Leonard, Mark V. Arena, Obaid Younossi, and Jerry M. Sollinger, 2008, *Sources of Weapon System Cost Growth Analysis of 35 Major Defense: Acquisition Programs*, MG-670-AF, Santa Monica, Calif. Total development and procurement cost growth for missiles averaged 43.9 percent for six programs. Development cost growth was reported at 40.6 percent, with the 17.5 percent of the 40.6 percent due to requirements changes, another 4.6 percent due to schedule changes, and the majority of the remainder of 15.2 percent due to cost estimating errors. The procurement cost growth average of 58.5 percent included 13.1 percent for requirements changes, 15.5 percent for schedule changes, and 5.5 percent for quantity changes with most of the remainder of 13.9 percent due to cost estimating errors.

funds identified in past fiscal year budget justification sheets, and (3) open source contract award prices as documented in *Defense Links*.

Table E-3 below is a representative reference list of MDA interceptors we used as the key reference data we used for generating our LCC range estimates along with key cost details listed in tables that follow later in this section along with representative sets of parametric data values collected for each.

TABLE E-3 Representative Sources of Cost Data

Interceptor Systems	Development (Non-Recurring Cost)	Production (Recurring Unit Cost	Annual O&S Cost	MILCON Cost
GMD systems[a]				
GBI	NMD and GBI and test details	Booster stacks (2 vs. 3 stage), booster avionics module (BAM), EKV, IA&T, long-lead parts	Total GMD system MDA, contractor and MILPERS sustainment costs and unscheduled and scheduled maintenance costs per GBI	Missile fields, utilities and mechanical/electrical buildings
Silos	Part of NMD total	Missile field 2 estimates, allocated on per silo cost basis		Silo ground infrastructure
IFICS data terminal	Part of NMD total	FGA configuration		Yes
Ground fire control	Part of NMD total	Common to FGA and MDIOC		N/A
Aegis[b]				
BMD 3.6.1				
SM-3 Block IA	Combined total	Yes	Per missile	N/A
Ship system (AWS)		Total only including installation cost	Per AWS	N/A
BMD 5.1				
SM-3 Block IB	Separate total	Yes	Per missile	N/A
Ship system (AWS)	Separate total	Total only including installation cost	Per AWS	N/A
BMD 5.1				
SM-3 Block IIA	Separate total	N/A	TBD	N/A
Ship system (AWS)	Separate total	Total only including installation cost	TBD	N/A
THAAD[c]				
System	Captured in RDT&E budget documents	Total procurement cost only (includes PSE, systems integration, GSE and CFE	Beginning in FY 2011, annual O&S cost per THAAD battery split between MDA and Army O&M and MILPERS budgets[d]	N/A
Interceptors	Part of system total	Yes		N/A
TFOC	Part of system total	Yes		N/A
Launchers	Part of system total	Yes		N/A
PAC-3	MDA and Army RDT&E and procurement budgets and latest selected acquisition report			N/A

NOTE: MDIOC, Missile Defense Integrated Operations Center; NMD, National Missile Defense; EKV, exoatmospheric kill vehicle; GBI, ground-based interceptor; IA&T, assembling, integrating, and testing; GSE, general support equipment; CFE, contractor furnished equipment; PSE, particular support equipment; O&S, operation and support; TFCC, THAAD Fire Control and Communications; AWS, Aegis weapon system.

[a] Benchmark cost for sea-based and ground-based X-band radar covered separately.

[b] Benchmark cost for SPY-1 radar covered separately.

[c] Benchmark cost for terminal-based TPY-2 radar covered separately.

[d] THAAD O&S annual costs are divided between MDA PTSS, sustaining support, government-furnished equipment (GFE) and support equipment modifications and logistics support of the interceptors, TFCC, and launchers. The Army O&S costs are comprised of POL, GFE spares, repair parts and depot maintenance and d indirect support.

ESTIMATING METHODS

Overview

The best estimating methods were selected based on compilation from one of the following:

- Analogous systems with comparable performance and/or technical parametric values or
- Cost models based on factors ranging from weight and power costs to statistically derived cost estimating relationships (CERs).

Cost models with sets of CERs were preferred; they were selected based on a set of technical parameters that best depicted and aligned with the logical set of cost drivers that directly impact the magnitude of the booster and propulsion missile system costs, missile IR seekers, ground radars, airborne and space-based EO/IR/FMV sensors, space launchers, cost per kilogram trends, and so on. In addition as part of the set of estimating methods, the committee used cost models that quantified cost sensitivity—in, for example, estimating space-based interceptors vs. ground-based interceptors and differences between airborne and space-based IR sensors.

Development Costs

In general, the primary approach used in estimating the rough order of magnitude of development costs was based on an analogous method where feasible. This approach relied on parametric cost models when needed or on a cross-check to ensure the overall reasonableness of the estimates. The parametric cost estimates used for both development and production cost estimates is summarized in Table E-4 below.

The analogous estimates were computed using historical costs from comparable systems and escalating them to FY 2010 constant year dollars. The costs were then adjusted based on applying an aggregate set of complexity factors primarily driven by a top-down subsystem, and estimates might be lower because of the extent to which the new system could leverage the technical design, engineering, and manufacturing heritage. The heritage assessments were expressed in terms of technology readiness levels (TRLs) or manufacturing readiness levels (MRLs), widely used indexes of maturity.[9]

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[9] William L. Nolte, USAF Air Force Research Laboratory (AFRL), Sensors Directorate. 2007. Hardware and Software Transition Readiness Level Calculator, Version 2.2, March 9. Available at www.acq.osd.mil/jctd/TRL/TRL%20Calc%20Ver%202_2. Accessed August 28, 2012. See also William L. Nolte, USAF AFRL,Sensors Directorate, 2002, AFRL Technology Readiness Calculator, October. Available at www.dtic.mil/ndia/2003systems/nolte2.pdf. Accessed August 28, 2012.

TABLE E-4 Summary of Parametric Cost Models

System or Subsystem	Parametric Cost Models
Interceptor stages	Basic rocket equations
Propulsion subsystems	Tecolote launch vehicle cost model NASA Marshall Space Flight Center (MSFC) Launch Vehicle Cost Model[a]
IR seekers	Galorath SEER-hardware and electro-optical systems (EOS)[b]
Airborne platforms	RAND DAPCA model[c]
Space-based platforms	Tecolote unmanned spacecraft cost model (USCM)[d] Aerospace small satellite cost model (SSCM)[e]
Radar	Technomics ground-based radar cost model[f]
Electro-optical sensors	Galorath SEER-hardware and electro-optical systems (EOS)[b]
Launch service costs	American Institute of Aeronautical Engineers (AIAA) International Launch Vehicle Systems Handbook, 4th edition[g]

[a] Tecolote Research, Inc. 1996. NASA MSFC, Launch Vehicle Cost Model, PRC Service, CR-0734, August 23. CERs for solid rocket motor, and liquid rocket engines, solid fuel systems, and so on.

[b] Galorath SEER-electro-optics (EO) parametric cost model.

[c] RAND Corporation, DAPCA aircraft cost model.

[d] USAF Unmanned Spacecraft Cost Model, eighth edition.

[e] Aerospace Corporation, 2002, Small Satellite Cost Model (SSCM).

[f] Technomics ground-based radar cost model; CERs taken from J. Horak, J. Harbor, and C. Holcomb, “Integrating Performance and Schedule Analysis with Acquisition Costing for Ground-Based Radars,” presentation to the committee, February 18, 2010.

[g] AIAA, 2003.

Production Costs

In general, the total production cost of each interceptor is calculated by estimating the first unit cost of each major component of the system and then by estimating the cost of assembling, integrating, and testing (AI&T) those components into the first interceptor off the production line. The components include the booster stage(s), avionics (electronic communications and navigation systems), the KV, and, for mobile interceptors, the launch canister. Unless there was a comparable early warning IR sensor, radar, or interceptor with known unit production cost details, the costs of the majority of the relatively new systems cost were based on system, subsystem, or lower level CERs from the parametric cost models listed in the above table.

Specifically, the booster portion of the interceptor costs that were not part of the MDA programs of record were estimated using a CER based on the total impulse (thrust multiplied by burn time) of each stage of a booster and other technical parameters to calculate the cost of the first production model of the booster. Costs for the booster’s avionics and KV’s avionics, divert attitude control system (DACS), thrusters and other hardware were estimated with the Air Force Unmanned Spacecraft Cost Model (USCM). USCM uses CERs based on the mass of various components. In addition, the space-based interceptor satellite configured with a lifejacket was estimated using USCM at the subsystem level.

“Wrap” factor percentage values were also applied for estimating the costs of IA&T for components, subsystems, or systems by adding the costs and applying a percent value to the total cost of an interceptor. Where applicable, a wrap factor percentage was also applied for estimating the cost of government systems engineering and project management (SEPM), which would add another 30 percent. The percentages and values applied in the roll-up of an interceptor (as well as other sensor system costs) are consistent with CERs most commonly used for such work.

As in the 2004 CBO report, "costs for the [remaining new] interceptors that would be purchased under each option were estimated by analyzing trends in actual costs for the ground-based" interceptors that MDA has recently purchased.[10] The average unit procurement costs computed for multiple interceptors reflects the impact of total manufacturing labor hours and of cost efficiencies of discounts on material quantities on the cost of the first interceptor or other system firsts. Costs would decrease as a function of the quantity produced within an assumed continuous single manufacturing run or of the inefficiencies of reopening and restarting a manufacturing line to procure more replacement interceptors. The estimate of unit production cost of additional interceptors is based on the learning curve, or cost improvement curve (CIC), or on a slope of the historical unit production cost of analogous interceptors as a function of quantity produced.[11] Details are provided in the next section of this appendix of the computed unit production cost for Aegis SM-3 Block IA and THAAD interceptors.

Sustainment Costs

Except for space-based interceptors (SBIs), the majority of the sustainment cost estimates are based on average annual O&S system costs provided by MDA program offices. As needed and for completeness, the average annual O&S costs for systems already delivered and fielded were cross-checked against the total MDA and services (i.e., Navy for Aegis and Army for Patriot) O&M system program budgets and portions of the RDT&E program budget justification sheets where material sustainment-related activities and associated funds were clearly identified. For SBIs, the sustainment costs were based on assuming an average on-orbit life for each SBI satellite of 7 years and included procurement replacements and launch costs to maintain full operational capability (FOC) over the 20-yr service life. The annual operating costs for ground mission control were based on previously estimated costs from the 2004 CBO report escalated to FY 2010 dollars.[12]

LIFE CYCLE COST DETAILS ON MDA NEW SYSTEMS

Aegis SM-3 Block IIA and Aegis Ashore Systems

In the FY 2012 PB MDA is currently requesting an RDT&E total budget of $2.7 billion through FY 2016 (in FY 2010 constant dollars) for the SM-3 Block IIA interceptor system and the Aegis Ashore programs of record and another $350 million for the procurement of the first 15 Block IIA interceptors, with first delivery expected in FY 2019. Projecting forward, the committee estimated 20-yr LCC that includes the requested budget to account for the potential deployment of these latest Aegis interceptors at both ship-based locations in the Persian Gulf and at land-based European or Middle East sites.

Table E-5 lists the total 20-yr LCC estimates for improved ship-based and land-based Aegis SM-3 Block IIA interceptors.

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[10] Congressional Budget Office. 2004. *Alternatives for Boost-Phase Missile Defense*, Washington, D.C., July.

[11] The learning curve, or CIC slope, value of, for example, 95 percent, quantifies the cost reduction associated with doubling the number of interceptors being purchased and reduces the average unit cost of the lot buy of interceptors by about 5 percent.

[12] Congressional Budget Office. 2004. *Alternatives for Boost-Phase Missile Defense*, July.

TABLE E-5 Improved Aegis SM-3 Block IIA Interceptor System LCC Estimates (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	2.0	3.0
Procurement	See above	See above
Force quantity buy[b]	Projected SM-3 Block IIA, quantity = 56 (mix of either two dedicated Aegis ships or two land-based sites)	
MILCON	0.10	0.10
20-yr O&S[c]	3.9	4.4
Total	6.0	7.5

[a] Based on the MDA FY 2012 FYDP RDT&E PM SM-3 Block IIA codevelopment and Aegis Ashore program budgets from FY 2010 through FY 2016. The development cost also includes the delivery of 29 SM-3 Block IIA interceptors covered as part of the RDT&E interceptor co-development program budget through FY 2016 and an additional procurement budget buy of 15 SM-3 Block IIA interceptors. The average unit cost of the SM-3 Block IIA missile round was listed in FY 2014 at $24.3 million.

[b] The procurement cost included in the development estimate is based on a force quantity buy of 48 operational SM-3 Block IIA missiles and an addition 8 test interceptors.

[c] The SM-3 Block IIA system O&S estimates are based on continuous operational readiness of 48 SM-3 Block IIA interceptors on a mix of two dedicated Aegis ships in either the Persian Gulf or at two Middle East fixed land sites with 24 operational missiles plus test interceptors at each location, all over a 20-yr sustainment period.

In addition to these sites with large coverage capability against Iranian IRBM/MRBM threats, a number of THAAD and/or PAC-3 batteries will also be needed for close-in defense against SRBMs near the forward perimeter of the defended zones. The 20-yr LCC summary estimates for these two systems are provided later in this appendix in the subsection after next for THAAD and for Army PAC-3/MSE Systems.

Aegis SM-3 Block IIB

MDA is requesting in the FY 2012 PB an RDT&E total budget of $1.6 billion through FY 2016 (in FY 2010 constant dollars) for the SM-3 Block IIB interceptor system program of record. Since the SM-3 Block IIB program beginning in FY 2011 is in an early technology development phase, MDA has awarded three contracts with potential prime contractors to define missile concepts, assess technology risk, and complete system-level trade studies in preparation for the product development phase, which is not scheduled to begin until FY 2013.

Even though previous performance interceptor funding combined with the propulsion technology content were used for the SM-3 Block IIB new program of record, it is too early in the acquisition to determine if the design baseline will focus on maturing the key component technologies to TRL values of 5 or 6 for increasing the speed of the missile (using lighter weight structures and materials to reduce inert mass) and ensuring the flexible energy management needed to effectively engage targeted ballistic missiles early in their trajectory. Other opportunities in the design trade space could include investments in advanced seeker technologies to increase KV acquisition range thus improving threat missile containment.

The engineering trade space includes alternative configurations for the booster to enable higher burnout velocities; larger diameter missiles and resulting modifications to the MK41 VLS launcher, rocket propellants, missile structures, control mechanisms, and missile communication concepts to enable communication with multiple sensors over several frequencies; kinetic warhead seeker and the kinetic warhead DACS. Another key aspect of the trade studies and technology development is to analyze and define a larger canister and missile threat that is compatible with the MK 41 launcher used on Aegis ships to ensure compatibility with Aegis Ashore and Afloat. This comprehensive strategy of technology investments to reduce risk, exploit technology opportunities, and engage industry early will provide the foundation for executable plans for the product development phase.

Given the current consideration of several land-based SM-3 Block IIB interceptor designs within the solution space from the original SM-3 Block IIB designs and projecting forward to a higher performance next-generation Aegis missile system (NGAMS), the committee estimated 20-yr LCC ranges to account for the technical risk and cost uncertainty in potential deployment of these latest AEGIS interceptors at land-based European sites.

Table E-6 lists the 20-yr LCC estimates for land-based SM-3 Block IIB interceptor systems for one dedicated European fixed site.

TABLE E-6 Land-Based SM-3 Block IIB System 20-Yr LCC Estimates (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	5.3	13.7
Procurement	See above	See above
Force quantity buy[b]	Projected SM-3 Block IIB, quantity = 28 (one dedicated European land site)	
MILCON[c]	0.10	0.10
20-yr O&S	3.8	5.5
Total	9.2	19.25

[a] The total development cost is based on total MDA FY 2012 RDT&E PB budget from FY 2011 through FY 2016 requested for the (1) land-based SM-3 Block IIB program, (2) BMD advanced technology development funds that were transferred to this program beginning in FY 2012, and (3) additional projected cost the committee estimated for extending the development phase for the lower bound, or minimum, total cost to FY 2019 and the upper bound, or maximum, total cost with the development program extended to FY 2021 and beyond.

[b] The procurement cost included in the development estimate is for a total force buy quantity for defending U.S. and European allies and U.S. deployed forces from an Iranian ballistic missile attack based on a total buy quantity of 28 SM-3 Block IIB missiles: 24 operational missiles and 4 test interceptors, ground-based launchers, fire control units, and C2BMC terminals at a single dedicated European land-based site.

[c] The MILCON cost is based on the MDA FY 2012 PB MILCON budget requested for the construction cost of a land-based SM-3 launch facility in the FY 2013 time frame.

Total SM-3 Blk IIB interceptor system O&S estimates are based on the costs for continuous operation readiness, testing and sustainment at one land-based European site for maintaining the 24 operational missiles and remaining test assets over a 20-yr period.

ABIR Systems

Life Cycle Cost Summary

A summary of the 20-yr LCC range estimate for the ABIR system is summarized in Table E-7.

TABLE E-7 ABIR System Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	1.4	1.9
Procurement[b]	0.3	0.7
Force quantity buy[c]	Three 24/7 CAPs of 3 + 1 spare or four mission-capable Reapers and a ground station per CAP	
	Total inventory of 12 vehicles for a notional annual use of up to 90 days per yr	Total inventory of 17 vehicles for a surge demand of up to 270 days per yr
MILCON	0.03	0.06
20-yr O&S[c]	2.6	2.8
Total 20-yr LCC estimate	4.2	5.4

NOTE: CAP, combat air patrol.

[a]The development cost estimate of between $1.4 billion and $1.9 billion is based on the MDA total investment in the ABIR program from FY 2011 through FY 2016 of $342 million as stated in the MDA FY 2012 FYDP and projected forward for another 9 to 14 years from FY 2023 through FY-2030 to complete EMD through full operational testing and continuing until go-ahead into the production phase. (Of the $342 million in ABIR program budget through FY 2016, $312 million is for the RDT&E development program and $30 million is MILCON budget for the construction of an ABIR facility in FY 2014.)

In addition, the development range estimates includes the cost of designing, integrating, and testing five fully configured flight test articles at a lower bound, or minimum, average unit procurement cost (AUPC) of $21.5 million for Reaper MQ-9Bs configured with an as-designed MTS-B sensor coming off the production line or at an upper bound, or maximum, AUPC of $24.5 million for a slightly modified MTS-B. The range for each ABIR system flight test article also includes an onboard processor and communications link to the C2BMC needed for satisfying and demonstrating the unique missile tracking performance required for the ABIR mission. The committee also estimated the AUPC of five sets of Reaper MQ-9 ground systems at $10 million each (in FY 2010 dollars) to be delivered along with airborne vehicles during the development phase. (Each Reaper ground system includes the procurement of hardware for the Reaper launch and recovery element for landings and takeoffs and the mission control station (MCS) for operating the vehicles once at cruise altitude and in on-station CAP orbits. The MCS includes the hardware and software interfaces to enable Reaper's ground operators to monitor the health and status of the airborne C2BM communications downlinks and ensure the integrity and timely transmission of the airborne IR sensor missile tracking data that is being routed to the nearest C2BMC and the designated interceptor's fire control radar.)

[b]For the follow-on production phase in FY 2023 to FY 2030, the procurement cost range estimate of between $300 million and $700 million is based on an ABIR system AUPC range for the force-level quantity of between 12 and 17 airborne systems. The committee based its procurement minimum cost estimate for an ABIR sensor AUPC integrated on a Reaper MQ-9B airborne vehicle configured with a modified MTS-B sensor at a lower bound, or minimum, AUPC estimated at $21.4 million for a lower bound force size of 12 airborne systems. The committee based the procurement maximum cost estimate for the same ABIR sensor AUPC integrated on a Reaper MQ-9B airborne vehicle configured with a notional repackaged, smaller, lighter, reduced-power-version of the pod-mounted Heimdall sensor as an alternative candidate IR sensor, also integrated on a Reaper MQ-9 airborne vehicle with a minimum AUPC estimate of $37.9 million for a higher force-level quantity of 17 systems. (The modified Heimdall sensor unit cost is based on a further weight, volume, and power reduction over the envisioned modifications needed for the Global Hawk RQ-4B. Further details on the earlier use of the Heimdall sensor and the basis for the modified version of this sensor are provided in a previous section of this appendix, "Aegis SM-3 Block IIA and Aegis Ashore Systems.") Finally, the procurement cost also includes three ground systems at $10 million each required for operating three CAPs at separate outside the continental United States (OCONUS) forward-deployed bases.

[c]The 20-yr O&S cost range estimate represents the steady-state annual O&S costs on a per CAP basis for operating and sustaining the ABIR systems and the ground segment operations centers out of a forward-deployed OCONUS base across the range of a force size inventory of up to (1) 12 systems for an average annual surge of CAP operations for 90 days, estimated at an annual cost of approximately $42 million per CAP, and (2) up to 17 systems for a higher annual surge of CAP operations for 270 days, estimated at an annual cost of approximately $47 million per CAP.

The basis for the forward-base locations, time to station, and other details used to compute the number of ABIR-configured Reapers to sustain a 24/7 CAP and the total force inventory quantity range of ABIR-configured Reapers needed for nominal and surge demand conditions are provided later in this section.

Previous Relevant Investments

As part of the potentially relevant (and technically relevant) proof-of-concept investment activities that preceded MDA submitting a budget for FY 2011 budget through FY 2015 for the new start ABIR program in February 2010, MDA has an on-going Airborne Sensor (ABS) program." The ABS program issued a request to industry in May 2009 for going forward with a 5-yr effort to continue "operation and sustainment of the MDA airborne sensors and platforms used to support the BMDS test program.[13] At that time, the contractor that won the award would "be required to perform mission operations, aircraft test operations, and aircraft maintenance [on four] airborne sensor systems currently operated by MDA[:] the High Altitude Observatories (HALO I, II, and III) and the Wide-body Airborne Sensor Platform (WASP) aircraft. . . .

The HALO I is a Gulfstream IIB aircraft with multiple sensors viewing through optical windows, used for data collection in the visible through long-wave IR (LWIR) spectral regions. Four sensor stations accommodate a mix of user-defined sensors in three gimbaled-mirror pointed platforms and one fixed-mirror pointed platform. HALO II is also a Gulfstream IIB aircraft with a cupola mounted atop the fuselage that allows for open port viewing with a multiband sensor system to collect radiometric and photo documentation data in the visible through LWIR spectral regions. HALO II also allows for window viewing by cabin sensors. HALO III is a Gulfstream IISP aircraft that serves as the airborne diagnostic target (ADT) for the Airborne Laser program. It includes a wing-mounted sensor pod, plume emulator, target board, various beacon lasers, and ADT system control and situational awareness hardware. WASP is a DC-10 aircraft modified with three pressure vessels to allow open port or closed cabin optical window sensor viewing. WASP will accommodate a prime sensor system (PSS) for data collection and guest captive-carry seeker/sensor systems. The WASP PSS is similar in design and capability to the HALO-II primary sensor."[14]

Furthermore, as a precursor to the ABIR program, the ABS program's industry solicitation also stated that "as future requirements emerge, MDA may add additional aircraft, additional sensors, develop new sensor systems, and/or modify sensor/mission support systems onboard the current [MDA] aircraft. . . . [MDA stated that] the intended outcome of this [solicitation was] to [both] "determine interest and capability" in supporting the ABS program and to identify acquisition alternatives that may warrant further study and review."[15]

In going forward and as part of its justification for the ABIR budget, MDA stated that in order "to address the looming threat of regional forces in large numbers, [it had] aligned [its] technology investments with [the objective of uncovering] gaps in [the] ability to (1) address large raid sizes and(2) intercept the enemy early in [its] trajectory [and] when the enemy is most vulnerable[:] assess[,] then reengage if necessary."[16]

In addition, to potentially leverage the relevant airborne IR and optics technology from the ABS program, MDA had prior to February 2010 "demonstrated the ability of IR sensors carried aboard Navy Reaper unmanned aerial systems to observe ballistic missiles in-flight at long distance during the `Stellar Daggers` test in Hawaii and the Delta II launch in California. The impressive results of these tests lead [MDA] to believe that airborne sensors can be an effective component of the Ballistic Missile Defense System as early as 2015."[17]

Going forward, the MDA total investment in the ABIR program, $477.1 million (FY 2010 dollars) reflects the average annual budget, $95.4 million (FY 2010 dollars), for the technology development effort to prove the airborne sensor capabilities and allow the operational

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[13] Airborne Sensor Program (ABS) Sources Sought, FBO Daily, May 22, 2009, FBO #2734, Notice date May 20, 2009, available at http://www.fbodaily.com/archive/2009/05-May/22-May-2009/FBO-01824078.htm. Accessed June 14, 2012.

[14] Ibid.

[15] Ibid.

[16] As reported in MDA, FY-2011 FYDP Research, Development, Test & Evaluation, President's Budget, Exhibit R-2, RDT&E Budget Item Justification, BA 4: Advanced Component Development & Prototypes (ACD&P), PE 0604884C: Airborne Infrared (ABIR), February 2010.

[17] Ibid.

assessment and proof of capability needed to detect ballistic targets and achieve early intercepts by conducting a series of ground and flight tests through FY 2012. Specifically, MDA stated that "these demonstrations [will] incrementally prove the key functions of an airborne infrared sensor:

- Acquisition of a threat based on a cue from overhead persistent infrared satellites;
- Tracking of a threat throughout its flight;
- Generation of a two-dimensional track prediction of the threat`s flight path based on a single airborne sensor;
- Fusing multiple two-dimensional tracks into a three-dimensional track with sufficient accuracy to launch an interceptor; and
- Delivering this information through the C2BMC system to the shooter. . . .

In FY 2010, [MDA] began assessing platform and sensor alternatives with MIT`s Lincoln Laboratory and partners at the Joint Integrated Air and Missile Defense Organization. This effort [pointed] the way to the [airborne] vehicle most suited to fill this role among a group of candidates including the currently deployed MQ-9 Reaper and the RQ-4 Global Hawk. At the same time, [MDA] [engaged the] Joint Forces Command and the COCOMs to develop a concept of operations for adding this mission to the [DOD's] unmanned aerial systems fleet."[18] The alternatives for the most likely platform and sensor combination were based on a cost-effectiveness assessment of the sensor's performance, target auto tracking, and raid handling capacity and on the airborne systems' secure communications data link capability to accurately transmit IR sensor data with low enough latency to enable C2BMC and BMDS interceptors to complete ballistic missile engagements.

Plans going forward include "computer-in-the-loop to hardware-in-the-loop experiments to incrementally verify and validate [the] functionality [of the airborne sensor's effective field of regard. According to MDA,] these experiments [will] culminate in Aegis intercept flight tests using primarily airborne sensors for fire control at the Pacific Missile Range Facility in Hawaii [planned for] the summer of 2012. This testing, interspersed with regular campaigns in theater, [leads] to [MDA's plans for] an operationally useful architecture as early as [FY] 2015."[19]

As far as estimating the recurring unit costs of the airborne platform and IR sensor mix system quantities, the planned schedule reported in the FY 2011 MDA ABIR program budget of February 2010, called for the first delivery of platform and ground station in the third quarter of FY 2011, followed by four other platforms and ground stations in 1-yr increments through FY 2015. MDA planned on modifying the first and second long lead in the first and fourth quarters of FY 2011. Since the program was to start in the first quarter of FY 2011, the committee assumes these airborne IR sensors are most likely MTS-B sensors already in production or a modified version of the MTS-B sensor. For estimating purposes, two other near-term key milestones are the launch of an ABIR system for performing an airborne sensor risk reduction demonstration, set for the third quarter of FY 2012, and plans for an acquisition procurement milestone decision by the second quarter of FY 2012 to procure operational assets for fielding in FY 2015.

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[18] As reported in MDA, FY-2011 FYDP Research, Development, Test & Evaluation, President's Budget, Exhibit R-2, RDT&E Budget Item Justification, BA 4: Advanced Component Development & Prototypes (ACD&P), PE 0604884C: Airborne Infrared (ABIR), February 2010.

[19] Ibid.

MDA Force-Level Quantities

For the purposes of estimating a recurring cost range for a representative unit during the procurement phase, the committee assumed a total MDA force-level quantity of at least 12 and a maximum of 17 airborne systems and the necessary three sets of ground stations that would be capable of sustaining eight mission-capable systems or primary authorized aircraft (PAA) operationally available for providing persistent 24/7 missile tracking coverage of up to three CAPs or one system per CAP. Each CAP and the two or three requisite PAA-designated systems are capable of being prepositioned and/or forward-deployed well in advance of the threat at OCONUS military bases located within a reasonable operating system range of the expected area of regard and within the effective range of the IR sensor for performing the missile tracking mission. The total force-level quantity also includes the procurement of three spares or backup inventory (BAI)-designated systems that are available as needed and colocated with each of the other PAA systems at one of the three OCONUS bases. The BAI-assigned ABIR systems are configured with the same airborne IR sensor as the PAA aircraft and are needed to maintain persistent operational coverage and used for replacing PAA-designated systems either in transit from the CAP back to the forward-deployed squadron or not operationally available until field maintenance is completed. Finally, based on a notional surge capability of three continuous CAPs on station for between 90 days and 270 days per year, the minimum and maximum range estimates of the total force-level quantity of ABIR systems is also based on procuring anywhere from one to six additional aircraft designated as attrition reserve inventory and needed to replace PAA systems due to operational attrition or other accidents, assuming, on average, the loss of two systems every 100,000 flight hours, where an in-flight accident occurred and/or the system was declared inoperable and too expensive to repair.

Table E-8 provides the ABIR system force-level quantity range estimates based on an average cruise speed of 175 mph at 40,000 ft and an average operational endurance of 24 flight hours per sortie.

System Acquisition Costs

Table E-9 summarizes the committee’s estimate of the ABIR System T1 recurring cost of the first of five airborne systems used during the development phase through FY 2015 for flight testing demonstrations and the projected cumulative average recurring unit costs for the procurement phase. The committee assumed that after FY 2015 the five flight test systems used during the development phase would end up being colocated at existing CONUS-based military test and training bases and used as test bed platforms for flight testing upgrades to an improved version of the MTS-B sensor and/or as a new, possibly more capable IR sensor for performing ballistic missile tracking missions on the Reapers acquired during the production phase.

For both the development and the procurement phase, the committed estimated the AUPC of the five flight article systems and the production quantity of between 12 and 17 ABIR systems based on Reaper MQ-9 unmanned aircraft configured with avionics, flight controls, and without mission payload hardware, as the preferred airborne platform.

For the 5-yr development phase currently funded in the FY 2011 budget through FY 2015, the committee estimated the IR sensor AUPC based of the first sensor delivered for the first Reaper to be an as-designed MTS-B sensor coming off the production line with a combination of either additional MTS-B sensors procured for the other four flight test airborne vehicles or a slightly modified version of the MTS-B designed to more closely satisfy and

TABLE E-8 Projected Force-Level Quantities for ABIR Systems

Force-Size Parameters	Reaper MQ-9
Representative distance base to CAP (mi)	621.4
Cruise speed (mph)	175
Notional endurance (hr)	32.0
One-way transit to fly-out and back (hr)	7.2
Time on station (hr)	24.8
Total flight hours per sortie	32.0
Sorties per day per CAP	1.0
Number of CAP forward-operating base locations	3
Total sorties per day	3
Sorties per day per aircraft	1
Total number of PAA-designated aircraft employed	3
BAI-designated aircraft per location	1
Minimum total force size of ABIR systems (assumes no attrition	6
Force flight hours per day (three CAPS)	72
Case 1: 90-day continuous three CAPS operation	
Total annual flight hours for 90-day surge	2,160
Average annual PAA-designated flight hours per aircraft per year	360
Attrition rate per 100,000 flight hours	2.0
Life-cycle flight hours (over assumed 15-yr service life)	32,400
Number of attrition reserve for 90-day surge (over 15 yr)	1
BAI-designated aircraft	3
Minimum total force size (with attrition)	10
Case 2: 270-day continuous three CAPs operation	
Total annual flight hours for 270-day surge	19,440
Average annual PAA-designated flight hours per aircraft per year	3,240
Attrition rate per 100,000 flight hours	2.0
Life-cycle flight hours (over assumed 15-yr service life)	291,600
Number of attrition reserve for 270-day surge (over 15 yr)	6
BAI-designated aircraft	3
Maximum total force size (with attrition)	15

TABLE E-9 ABIR System AUPC Estimate During the Development Phase (FY 2010 million $)

	ABIR System T1 Estimate
Reaper MQ-9 unit flyaway price	15.2
MTS-B sensor unit cost	0.9
Onboard mission processor and BLOS C2BMC	0.4
System AI&T (30 percent factor	5.0
Total ABIR T1 cost	21.5

demonstrate the unique missile tracking performance needed for the ABIR mission. In addition, the costs for adding an onboard mission processor and C2MB communications to the Reaper MQ-9 are also included along with AI&T of each ABIR system.

For the follow-on production phase beginning after FY 2015, Table E-10 lists the ABIR AUPC range estimate for the force-level quantity of between 12 and 17 airborne systems. The committee based its range estimate of the ABIR sensor average unit cost on a modified MTS-B sensor as a lower bound for the lower bound force size of 12 airborne systems. As an upper bound recurring cost and as a potential hedging strategy for meeting the expected missile tracking requirements, the committee estimated the unit recurring cost of a notional repackaged

TABLE E-10 ABIR System AUPC Estimate During the Production Phase (FY 2010 million $)

	ABIR System AUPC Estimate	
	Low (Quantity = 12)	High (Quantity = 17)
Reaper MQ-9 unit flyaway price[a]	15.2	15.2
Modified MTS-B sensor unit cost[b]	1.2	
Modified Heimdall sensor unit cost[c]		11.8
Onboard mission processor and BLOS C2BMC	0.1	0.1
System AI&T (30 to 40 percent factor[d]	4.9	10.8
Total ABIR AUPC cost	21.4	37.9

[a] In the FY 2011 through FY 2015 time frame, the Reaper MQ-9 unit fly-away price is based on the assumption that MDA will be able to procure the as-is designed green aircraft off the contractor's manufacturing line fully configured with the flight controls, avionics, and other equipment to flight qualify the system. The price also included the communication system links for operating the unmanned vehicle through ground operators at the launch and recovery unit and the missions control station and also for transmitting the IR sensor data through MDA's C2BMC and on to a designated interceptor's fire control radar. After FY 2015 MDA will be procuring identically configured Reapers coming off a mature, continuous production line, where it assumed the learning or cost improvement factor is relatively flat and affords relatively small savings per system as the total quantity manufactured increases.

[b] The modified MTS-B sensor is based on a more complex design than the MTS-B, that provides additional IR capability to meet the mission-unique requirements for performing the missile tracking mission.

[c] The modified Heimdall sensor unit cost is based on a further weight, volume and power reduction over the envisioned modifications needed for the Global Hawk RQ-4B. ABIR system analysis alternatives performed for MDA indicated that the Heimdall sensor suite and real-time signal processors onboard the HALO II aircraft can be transplanted to fit within a configured green aircraft version of the Global Hawk RQ-4B without any other mission equipment. However, the RQ-4B airframe must be able to accommodate the weight load of the pod and the necessary onboard electronics. Given the existing RQ-4B onboard power and air cooling and further modifications needed, the total weight load on the RQ-4B of a pod-modified Heimdall sensor was estimated at between 2,000 lb and 2,800 lb, with more than 700 lb of this weight attributable to the optical sensor, the platform, and the mission equipment suite itself.

[d] The factor for IA&T for the Heimdall IR sensor is higher, 40 percent, than that for the modified MTS-B sensor reflects because the recurring costs of electrical and mechanical interfaces to install this heavier sensor and still meet the platform's center of gravity and reduced drag requirements will be higher.

and smaller, lighter, and reduced-power version of the pod-mounted Heimdall sensor (compared to the option MDA had considered as a candidate IR sensor for the Global Hawk RQ-4B). (The full-scale Heimdall sensor was originally designed for and is currently being used on the HALO II manned ABS testbed aircraft.) It should be noted that this upper bound, higher ABIR system recurring cost estimate would most likely require additional development funds to cover the cost for modifying the Reaper airframe to carry the load of the larger pod-mounted IR sensor and still meet the aerodynamic performance and required high endurance of the vehicle. The upper bound estimate is also based on the higher force-level quantity of 17 systems.

The committee also estimated the average unit cost of five sets of Reaper MQ-9 ground systems at $10 million each (FY 2010 dollars) to be delivered along with airborne vehicles during the development phase. Since this procurement relies primarily on off-the-shelf computer workstations, processors, and communication equipment, the committee estimated the cost of operating three CAPS at separate OCONUS forward-deployed bases would remain at $10 million each for the procurement of three ground systems required during the production phase. Each ground system requires the procurement of hardware for the Reaper launch and recovery element (LRE) for landings and takeoffs and for the mission control station (MCS) for operating the vehicles once at cruise altitude and for on-station CAP orbits. The MCS includes the hardware and software interfaces to enable Reapers' ground operators to monitor the health and status of the airborne C2BMC downlinks and to ensure the integrity and timely transmission of the airborne IR sensor missile tracking data to the nearest C2BMC and the designated interceptor's fire control radar.

System O&S Costs

Finally, Table E-11 provides a rough order-of-magnitude range estimate for the steady-state annual O&S costs on a per CAP basis for operating and sustaining the ABIR systems and the ground segment operations centers out of a forward-deployed OCONUS base for force sizes of 12 systems (for an average annual surge of CAP operations for 90 days) and 17 systems (for a higher annual surge of CAP operations for 270 days).

TABLE E-11 ABIR System Average Annual Sustainment Cost for Force Sizes of 12 and 17 for Three CAPS (FY 2010 million $)

	ABIR (Reaper MQ-9) Average Annual O&S Costs per CAP	
	12	17
Unit level manning	13.58	13.58
Operation and consumption[a]	10.10	14.31
Nonoperating unit maintenance	1.07	1.07
Sustaining support and investment	15.03	15.03
Indirect and other costs	2.84	2.84
Total average annual O&S cost per CAP	42.63	46.84

[a] The annual O&S cost per CAP for the large force size of 17 systems and the associated higher average annual flying hours per CAP case is the only O&S cost element that directly affects the magnitude of the ground operations and spare parts consumption costs at both the field and depot levels of maintenance. All the other O&S costs elements for the manning levels at the forward-deployed OCONUS squadrons are assumed to be fixed for both cases, along with the other three cost elements listed.

PTSS Systems

Life Cycle Cost Summary

A summary of the 20-yr LCC range estimate for the PTSS space and ground segment system is summarized in Table E-12. Further details on the basis of the estimates and further breakout of costs for all three phases of the life cycle are provided in this section.

TABLE E-12 PTSS Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	3.1	4.5
Procurement[b]	4.4	6.9
Force quantity buy	9-ball constellation + two on-orbit spares with 7 yr on-orbit life	12-ball constellation + two on-orbit spares with 5 yr on-orbit life
MILCON	None required	None required
20-yr O&S[c]	10.7	25.6
Total 20-yr LCC estimate[c]	18.2	37.0

[a] The development cost range estimate of $3.1 to $4.5 billion includes the PTSS program budget of $1.3 billion cited in the MDA FY 2012 FYDP PB, which consists of a 1-yr concept development phase beginning in FY 2011 awarded to three contractors followed by a Phase I effort with plans for developing, launching, and operating a set of first spacecraft articles using an integrated ground control system in FY 2016. The estimate for the Phase I effort consists of the total nonrecurring development and recurring costs for designing and building the space segment bus, the optical tracking and communications payloads for two prototype satellites, and the ground segment. The PTSS prototype satellites will demonstrate early, precise, real-time tracking of ballistic missiles.

As part of the development cost and as the basis for the procurement cost of the first production satellite, the committee estimated the recurring cost of producing the first two prototype satellites at $550 million each (FY 2010 dollars) based on (1) applying PTSS weight and power budget estimates at the satellite bus and payload subsystem levels to two parametric representative space system and electro-optical cost models and (2) using each model's cost estimating relationships calibrated to previous analogous cost expenditures and comparable parametric data details from the STSS program at the same subsystem detail for the development build of two prototype satellites. (The MDA PTSS program office provided the committee with a spreadsheet for PTSS Phase I annual budget costs and weight and power estimates for the prototype satellites as of May 2010. The two estimating tools used were the USAF Unmanned Spacecraft Cost Model (USCM) 8th edition and the Galorath SEER EOS parametric model. The cost estimating relationships of the two cost models have been calibrated against the STSS program's recurring costs and weight and power and other parametric data values reported in the March 2010 STSS Cost Analysis Requirements Description (CARD)).

The MDA budget through FY 2016 does not include the launch vehicle (LV) and LV adapter costs or the costs for the space segment contractor's prototype mission integrated system engineering team efforts at the space launch pad to IA&T and full functional checkout of the two prototype satellites in a stowed configuration onto the upper-stage shroud of the heavy lift launch vehicle. The committee included the launch booster, launch services, and space segment contractors' launch IA&T and checkout costs in development cost estimate. The total launch cost during the development phase is based on launching the two prototype PTSS satellites on one Atlas V EELV-class booster capable of lifting both, each with an estimated satellite total wet mass of 1,550 kg, which includes 30 percent weight margins for the both the PTSS bus and the payload.

[b]The procurement cost range estimate of $4.4 billion to $6.9 billion is based on the follow-on build of an additional 9 to 12 satellites (which includes two on-orbit spares) and an AUPC range estimate for each PTSS satellite of $452 to $572 million. The PTSS satellite AUPC range estimate for the lower bound, minimum, reference data point is based on a best case step-down in the second prototype satellite cost for the first unit cost of the production satellite designed for a 7-yr expected design life. This estimate is then projected forward for the total build quantity required to reach FOC of a 9-ball constellation based on a highly efficient cost improvement, or learning curve, of 95-98 percent. The committee based an upper bound, maximum, AUPC estimate using a worst case, or minimal, step-down in the second prototype satellite for the first unit cost of the production article designed for a 5-yr expected design life and then projected forward for the total build quantity required to reach FOC of a 12-ball constellation based on very little or no cost improvement (a flat learning curve). As in the development phase, the launch cost range estimates are assumed to be the same for the two prototype satellites based on an EELV-class vehicle capable of lifting two production satellites per launch.

[c]The 20-yr O&S cost range estimate covers the fixed costs for the ground segment infrastructure and personnel needed beginning with the first two prototype satellites on orbit and continuing forward for the production of on-orbit satellites within the constellation for the following tasks: (1) on-orbit satellite station-keeping and maintaining tracking, telemetry, and communications, and (2) mission command and control (C2) needed for passing on satellite precision tracking data for augmenting the planned terrestrial sensor network.

The O&S cost range estimate also includes the cost of producing and launching the additional replacement satellites needed for sustaining the constellation size, where (1) the lower bound, or minimum, cost estimate is based on sustaining the 9-ball constellation based on satellites with an expected average on-orbit life of 7 years, and (2) an upper bound, or maximum, cost estimate is based on sustaining the 12-ball constellation based on satellites with an expected average on-orbit life of 5 years.

Relevant Investment Costs

As of May 2010, the projected investment cost beginning in FY 2011 and continuing through FY 2016 is $1.3 billion (constant FY 2010 dollars). According to MDA, this investment and the annual budget investment of $217 million reflects a 1-yr concept development phase beginning in FY 2011 followed by a Phase I effort beginning later in FY 2011, with plans for delivery and launch of two prototype satellites by late FY 2015. The prototypes "will demonstrate early, precise, real-time tracking of ballistic missiles.[20] The cost includes the estimated budget for FY 2016 of the Phase I effort to cover the costs for operating the two prototype satellites and augmenting the "planned terrestrial (surface and airborne) sensor network . . . with [a demonstrated] precision tracking [capability] from space."[21]

The investment costs are based on the MDA PTSS program budget estimates as of May-2010. The program budget request for FY 2012 at the time was still under development so the budget had yet to be determined. The PTSS Phase I annual program budget estimates through FY 2016 consist of all nonrecurring development and recurring cost estimates for the space segment bus, the optical tracking and communications payloads, the ground segment, the launch vehicle (LV), and LV adapter costs as well as the costs for the contractor's prototype mission integrated system engineering team, system engineering program manager, the space segment IA&T, and the operations and testing of the prototype satellites. The roll-up of the total annual budget also included an estimate of the government program operations costs. The MDA PTSS program office provided a spreadsheet of PTSS Phase I annual budget costs and weight and power estimates of the prototype satellites. The development cost budget has been updated since May 2010 to reflect two February 2011 documents: "MDA Fiscal Year 2012 Budget Outline" and "FY 2012 Appropriations Summary," RDT&E PTSS program element line item budget from 2011 through FY 2016.

System Acquisition Costs

For the purposes of estimating the recurring cost of prototype and an operational projected baseline constellation of nine PTSS satellites, the committee reviewed the MDA's PTSS Phase I program budget projection and span time frame of 5 years from the start of concept definition through delivery and launch of the first two prototype satellites as the best case, or lower bound, estimate of $1,058 million (in FY 2010 dollars) through the end of FY 2015. Based on the best available analogous comparison of the STSS program's expended average annual costs and development time frames reported in the STSS CARD document from March 2010[22] and the most recent STSS program percent cost growth reported by GAO,[23] the committee derived an upper bound PTSS Phase I estimate of $1,354 million (also in FY 2010 dollars) based on a representative SSTS program cost growth of 28 percent over the 7 years of development span time beginning in April 2002, when MDA took over the Air Force SBIRS Low program and the contractor team had authority to proceed through the refurbishment and

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[20] See MDA, FY-2011 FYDP Research, Development, Test & Evaluation, President's Budget, Exhibit R-2, RDT&E Budget Item Justification, BA 4: Advanced Component Development & Prototypes (ACD&P), PE 0604883C: Precission Tracking Space System, February 2010.

[21] Ibid.

[22] MDA. 2010. "Space Tracking and Surveillance system (STSS) Demonstration Satellites" Cost Analysis Requirements Description (Card), March 1.

[23] GAO. 2010. "Report to Congressional Committees–Defense Acquisitions: Assessments of Selected Weapon Programs," GAO-10-388SP, March.

launching of the two STSS demonstrations satellites in September 2009,[24]

The committee was able to derive the first unit (T1) costs for the first prototype satellite based on first parsing out the Phase I space segment recurring portion of the costs from the MDA-provided Phase I annual program budgets. This was done by assuming that the Phase I portion of the nonrecurring Phase I development prototype time frame is a best case (optimistic) estimate comparable to the STSS program's time frame of slightly less than 2 years (23 months) from the MDA contractor team's ATP in April 2004 through prototype satellite concept design review (CDR) in March 2004.

Table E-13 provides a summary of our PTSS T1 prototype satellite unit cost and the projected cumulative average unit costs for the Phase II procurement of a constellation of nine on-orbit satellites and two spares.

TABLE E-13 PTSS Satellite Recurring Unit Cost Estimates (FY 2010 million $)

	T1 Prototype Satellite Cost		Cumulative Satellite Cost (9-Ball Constellation)	
	Low	High	Low	High
Total PTSS satellite unit cost[a]	198.1	250.5	148.9	187.8
Government office/program operations	10.9	10.9	9.8	9.8
Contractor satellite unit cost	187.2	239.6	139.1	178.0
PTSS	0.1	0.1	0.1	0.1
SE/PM	23.2	29.8	17.3	22.1
IA&T (space segment)	29.1	37.2	21.6	27.6
Space segment	110.8	141.8	82.3	105.3
Bus	55.0	70.5	38.3	49.1
Payload	55.7	71.3	43.9	56.3
Optical tracking P/L	34.0	43.6	26.8	34.4
Communications P/L	21.7	27.8	17.1	21.9
Operations and test	24.0	30.7	17.8	22.8

NOTE: P/L, payload; SE/PM, system engineering/project manager

[a] The cumulative average unit costs for the space segment bus are based on first starting with a step-down cost of 10 percent from the second prototype satellite cost to the first production unit cost, and then projecting forward a cumulative average unit cost for a total of 11 satellites based on a 95 percent representative cost improvement factor for bus production. The same 10 percent step-down factor is applied to the first production unit cost for both PTSS payloads and then a cumulative average unit cost is projected for a total quantity of 11 satellites based on a slightly higher 98 percent learning curve factor for payload production.

MDA's May 2010 PTSS Phase I annual program budgets submitted to the committee also included a program launch cost estimate of $145 million (in FY 2010 dollars) based on launching the two prototype PTSS satellites on an Atlas V based on a total wet mass estimate of 1,550 kg, which includes 30 percent weight margins for the bus and the two payloads.

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[24] This upper bound estimate is based on GAO reporting in March 2010 that MDA STSS program office officials stated that there were 2 years of prototype satellite launch delays, and over the MDA period of performance contract costs increased by 40 percent, or $385 million, which included about $115 million to address the various hardware issues that drove the launch delays. Since there was a 3-year gap in the STSS program in the transition from the Air Force to MDA and the majority of the development was focused on the STSS satellites' refurbishment, the committee reduced the cost growth due to the added costs for resolving hardware issues that resulted in launch schedule delays and assumed 28 percent was a more representative cost growth factor for estimating the upper bound PTSS Phase I program cost. The committee used this same 28 percent cost growth factor for estimating the upper bound or high estimates for the T1 PTSS prototype satellite cost and the Phase II average recurring unit costs of the constellation of operational satellites.

System O&S Costs

Since this PTSS represents an MDA new start program that begins with the concept definition phase, the committee estimated the average annual sustainment costs as a rough order of magnitude (ROM) annual projected O&S cost of between $66 million and $108 million (in FY 2010 dollars). The low estimate is based on the MDA PTSS program office's annual budget projection for FY 2016, which represents the fiscal year immediately following the planned launch of the two prototype satellites. The primary cost is for sustaining systems engineering and program management and ground segment operations. The upper bound, or high, estimate is based on the SSTS budget request for FY 2011 for testing the two on-orbit demonstrations, executing critical engagement conditions, and collecting test data used in updating, verifying, and validating the modeling and simulation representations used for assessing system performance. After completing the Phase II production, delivery, and successful launch of the nine-ball PTSS constellation so that it achieves FOC, the steady-state annual average sustainment costs for the system should consist of (1) ground segment operations centers for satellite on-orbit operations comprising station keeping, telemetry tracking, and health monitoring and (2) mission control centers for managing and directing on-orbit satellites' sensor data-link interfaces to interceptor fire control radars through the BMDS C2BMC communications network. The average on-orbit life of satellites is assumed to be the 5-yr design life.

FURTHER COST DETAILS FOR OTHER SYSTEM ALTERNATIVES CONSIDERED

Air-Launched Hit-to-Kill Systems

This section provides LCC range estimates for the development, procurement, and O&S costs of air-launched hit-to-kill (ALHK) interceptor missiles and associated airborne platforms based on the two Air Force/MDA design concepts the committee assessed as best able to meet the requirements for longer ranges and having a higher burnout velocity than the network-centric airborne defense element (NCADE) and air-launched PAC-3 missile concepts that have also been considered by MDA. At the time the committee was briefed by the Air Force/MDA back in July 2010,[25] the MDA ALHK study team had not recommended one specific interceptor—kill vehicles or airborne platforms with onboard sensors—over another for development.

Life Cycle Cost Summary

Table E-14 summarized the ALHK Interceptor system 20-yr LCC range estimate at between $10.5 billion and $17.6 billion. A more detailed breakout by LCC phase is provided later in this section, as are further details on the basis for these estimates.

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[25] Linton Wells III, MDA/DE, and Lt Col Jordan Thomas, USAF/A5XS, "Air Launched Hit-to-Kill in Ballistic Missile Defense Study," presentation to the committee, July 16, 2010.

TABLE E-14 Air Launched Hit-to-Kill Interceptor System Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	2.8	5.4
Procurement[b]	7.6	11.2
Force quantity buy	1,000 interceptors with 18-in. boosters and modified SM-3 Block IB KV and 100 retrofitted F-15Cs	1,000 interceptors with 18-in. boosters and advanced KV and 100 retrofitted F-15Cs
MILCON	None required	None required
20-yr O&S[c]	0.11	0.97
Total 20-yr LCC estimate	10.5	17.6

[a] The ALHK interceptor development program cost range estimates of between $2.8 billion to $5.4 billion (in FY 2010 dollars) over 12- and 15-yr time frames is based on going forward from technology development through the systems development and demonstration (SDD) phases for two ALHK interceptor missile options. As part of the SDD phase estimate, the development cost includes the procurement and flight testing of two advanced targeting pods installed on two F-15C test bed fighters configured with the existing onboard AN/APG-63(V)3 radar and either a LITENING or SNIPER targeting pod.

The SDD phase costs consists of estimates for the F-15C-unique development activities and for the concurrent design, integration, and testing of the ALHK missiles into two F-15C test bed aircraft.

The upper bound, or maximum, development estimate includes a contingency cost for mitigating two known risk reduction items and potential long-poles in the tent relative to beginning the SDD phase for demonstrating (1) airborne IR stereo ranging of ballistic missiles with two or more fighters flying in formation with the same sensor suite and (2) airborne Link-16 communications package integrated with BMDS off-board sensor systems (e.g., the proposed ABIR transmitting cueing target object map updates to the ALHK booster via the onboard fire control unit prior to KV vehicle separation.

The SDD range estimates include the costs of designing in airframe design modification for (1) retrofitting at least two F-15Cs as flight test articles to accommodate the weapons carriage loads of each missile option, (2) designing modifications to the fighter's existing stores management system, and (3) the additional system design engineering required to accommodate, integrate, and test either the LITENING G4 or the SNIPER surrogate pods on the two test bed fighters. Consistent with the Air Force/MDA briefing to the committee, the committee assumed the two F-15C fighters would be taken from the existing Air Force active fighter inventory or inactive (soon to be retired) drawdown fighter force.

[b] The procurement retrofit range cost estimate of between $7.6 billion and $11.2 billion is based on an estimated AUPC for both ALHK missile options, $7 million and $8.3 million, and a range estimate of the average retrofit recurring cost per F-15C of between $6 million up to approximately $29 million for accommodating either a LITENING G4 pod or a SNIPER surrogate pod.

[c] The total O&S marginal cost range estimate for sustaining 100 retrofitting multimission F-15Cs over the 20-yr service life of between $116 million and $966 million is based on an average marginal annual O&S cost estimate per CAP of between $0.2 million and $1.3 million.

System Acquisition Costs

Given the early concept design stage that MDA is currently in for evaluating the ALHK and airborne platform options, the committee felt it was prudent to generate two sets of range estimates based on two ALHK single-stage interceptor descriptions that MDA described to the committee back in July 2010 for use on either exo- or exo/high endoatmospheric engagements. The committee concurred with MDA that both proposed missile design concepts of larger missiles are technically viable and capable of providing longer standoff ranges and engagement during the ascent phase.

The first design comprised of an 18 in. diameter booster with an advanced kill vehicle (AKV) having an estimated total mass of 754 kg and a burnout velocity of approximately 3.5 km/sec. The second design alternative is configured with same size booster diameter and interceptor length but with a SM-3 Block IB KV-based design that has a higher projected burnout velocity, up to 4.1 km/sec. The estimated total mass of the second design alternative is 713 kg. Both ALHK interceptor design will require an integrated fire control unit.

MDA has looked at several airborne platform alternatives. The magnitude of the estimates for development cost and recurring retrofit cost of each mix of airborne platform and interceptor candidates is driven by the following characteristics of the air vehicle:

- Carriage capacity and maximum load (i.e., distributed total missile mass);
- Aerodynamic concerns raised by drag penalties, center-of-gravity related issues, reduced range, increased fuel consumption, and the like; and
- Overall launching capability at the optimal altitude, for each platform and each interceptor.

Manned fighter alternatives have sufficient carriage capacity for at least two interceptors per fighter for either interceptor option. Depending on the candidate fighter selected, MDA may be able to leverage to some extent off existing onboard sensors and radar with modifications as necessary for performing fire control capabilities. Manned bombers can carry the largest magazine (up to 24 on a B-1) but will require more significant changes to onboard sensors and fire control for performing independent ballistic missile defense missions. Currently developed remotely piloted aircraft (RPA) (formerly known as unmanned airborne systems, or UAS) are limited to carrying NCADE interceptors on the MQ-9 Reaper. Similar to fighters, the large-class of RPA may be able to leverage to some extent off existing onboard sensors but will require radar modifications to perform fire control functions.

From the perspective of a candidate airborne platform onboard sensor, MDA stated that target management should be handled by the same operational methods used in multitarget air-combat missions using a combination of onboard search radars with IR-assisted laser ranging and IR search and track (IRST) sensors for stereo ranging. This consists of using onboard (1) RF and IR sensors to conduct surveillance and make measurements and (2) processors to collect data, develop stereo tracks, allocate and assign interceptors, upload engagement instructions, direct interceptors, direct sensors, and conduct hit assessments.

The MDA design concept study team considered the following radars: F-15C AN/APG-63(V)3, F-15E AN/APG-82(V)1, and F-22 AN/APG-77. The airborne radar selected should complement the all-weather boost-phase capability of the ALHK missile and be capable of demonstrating the potential for providing real-time TOM in-flight updates after missile launch and for communicating and guiding interceptors to predicted intercept points.

The onboard airborne IR sensors contribute to tracking above the clouds or in their absence. Airborne IR sensor technology can detect a threat in boost at line-of-sight (LOS)distances. Current fighter IR sensors are range-limited to detect a separated reentry vehicle (RV). The F-35 distributed aperture system (DAS) has less detection distance than current SNIPER and LITENING pods for detecting ballistic missile threats after separation.

To establishing a cost baseline for each ALHK interceptor missile option, and consistent with the Air Force/MDA briefing, the committee selected the F-15C as the common airborne platform configured with the same onboard augmented sensor suite. The committee set the cost baseline for the set of sensors required on the Air Force/MDA set of projected performance projections and other assumptions provided in the briefing.

For an airborne intercept in boost phase, the Air Force/MDA assumed surveillance would be performed with airborne radar seeing through the clouds and/or with onboard infrared search and track (IRST) sensors. This combination of radar and IRST sensors would also be capable of detecting, tracking, classifying, and predicting the ballistic missile trajectory and uploading instructions to the interceptor missile.

To employ a shoot-look-shoot airborne intercept capability, the committee estimated the cost of developing a kit for ALTK missile system modification and the cost of recurring procurement retrofit as ranges, with the lower bound, or minimum, cost baseline consisting of using the existing F-15Cs able to carry a weapons load of two 18-in. boosters with a KV similar to the SM-3 Block 1B design; the onboard existing AN/APG-63(V)3 radar with the airframe would be retrofitted only as needed to accommodate the size, weight, and power (SWaP) required for installing an already designed and in-production LITENING G4 pod.[26]

The upper bound, or maximum, cost baseline estimate is for the following:

- Same F-15C airborne platform with the capability to carry two 18-in. boosters of an advanced KV design and onboard existing AN/APG-63(V)3 radar and
- Airframe retrofitted only as needed to accommodate the SWaP required for installing a SNIPER surrogate pod design needed for meeting the higher end performance range projected in the USAF/MDA briefing.

For this maximum cost baseline configuration, the committee assumed that the costs of developing a nonrecurring modification kit and of recurring procurement retrofit of the SNIPER surrogate pod would have to cover modifying the existing SNIPER Extended Range (XR) Advanced Targeting Pod (ATP).[27]

The development cost is for configuring F-15Cs will vary. They could range from revalidating and using the same previously designed modification kits for installing the LITENING G4 system to modifying the existing SNIPER XR ATP system and the newly designed modification kits for installing the SNIPER surrogate system on the F-15C. For both IRST systems, integration and testing with F-15C flight test articles will be required to ensure that the unique ballistic missile performance tracking requirements have been met before proceeding with production.

According to the Air Force/MDA briefing, the current development investment commitment focuses on advanced technology efforts. A decision on Materiel Development led by the Air Force Materiel Command involved funding in FY 2010 at $300,000 (in FY 2010 dollars). An Air Force/MDA Joint Concept Technology Development (JCTD) effort awarded two contractor proposals for development of an Air National Guard NCADE concept with funding estimated at approximately $40 million over a 3-yr period beginning in FY 2011.

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[26] In November 2008, the Air Force began ordering the LITENING next-generation (G4) targeting sensor system under a contract with the 647th Aeronautical Systems Squadron. (See Northrop Grumman press release: “Northrop-Grumman Receives $120 Million Order to Supply LITENING Gen 4 Targeting Sensor Systems,” *Global Newswire*, September 25, 2008.) This contract was followed by an additional order from the Air Force for 99 new LITENING G4 pods and 241 modification kits for installation and/or retrofit on F-15s as well as other fighter and attack aircraft. The LITENING G4 is the basis for the Air Force’s LITENING-SE. It includes an all-digital 1024 by 1024 pixel forward-looking IR sensor; a laser targeting program with improved target recognition across a wide range of conditions; and a plug-and-play data-link system that accepts a wide variety of off-board data links without further modifications.

[27] In August 2001, the Air Force awarded a contract under its Advanced Targeting Pod—Sensor Enhancement program to Lockheed Martin for procurement of the SNIPER XR ATPs. The buy of up to 522 pods was for the product and deployment on Air Force F-15CJ Block 50 aircraft and Air National Guard F-15 Block 30 aircraft. The delivery of 24 systems per year began in FY 2002 and ended in FY 2008. (See “Sniper XR/ATP—Advanced Targeting Pod,” Global Security Web site.)

The ALHK Interceptor development program cost range estimates of between $2.8 billion and $5.4 billion (in FY 2010 dollars) over 12- and 15-yr time frames for going forward from technology development through the SDD phases, along with the time frame range estimates for each phase for the two ALHK interceptor missile options are summarized in Table E-15. As part of the SDD phase estimate, the development cost includes the procurement and flight testing of two advanced targeting pods installed on two F-15C test bed fighters configured with the existing onboard AN/APG-63(V)3 radar and either of the previously described LITENING or SNIPER targeting pods.

Consistent with the basis for the cost range estimated for the SDD phase, the committee assumed the procurement retrofit range cost estimate for accommodating either a LITENING G4

TABLE E-15 ALHK Interceptor Program Development Cost Estimates (FY 2010 billion$)

	Development Cost[a]		Air Force/MDA Description of Development Phase Effort and Missile TRL Assessments[b]		Development Time (Yr)[c]	
Cost Component	Minimum[d]	Maximum[e]			Minimum[c]	Maximum[f]
Fighter/ALHK Cost Benefit Study[g]	0.001	0.008	Conduct detailed BMDS cost/benefit analysis.		0.5	1.5
F-15C unique technology development (risk reduction phase)[h]	0.3	0.4	Airborne demonstration of in-formation IR stereo imaging and off-board Link-16 communications with BMDS sensors.		3	3
F-15C unique SDD phase[d]	0.5	0.7	Integrate new sensors, fire control S/W dev, flight tests and stores separation.		3	3
SDD phase and ALHK missile options[e]			Intercept only	ALTK application		
18-in. booster with SM-3 Block IB KV	2.1	3.2	3	3	8.5	10
18-in. booster with advanced KV	2.9	4.4	3	3	9	10.5
Total development cost	2.8 to 3.5	4.3 to 5.4		Total time frame (yr)	12 to 12.5	14.5 to 15

[a] The development cost range estimate listed is for two acquisition phases, technology development and SDD; the latter phase costs consist of estimates for (1) the F-15C unique development activities and (2) the concurrent design, integration, and testing of the ALHK missiles into two F-15C test bed aircraft.

[b] For each ALKK missile option, the committee assumed the same assessed value for the TRLs that the Air Force and MDA cited as one of the primary factors for driving both the nonrecurring portion of the SDD costs and the time frame for development from Milestone B contract go-ahead through the modified fighter ALHK Interceptor missile system's critical design review (CDR).

[c] Consistent with the minimum development cost estimates, the minimum time frames listed for the technology development and SDD are consistent with the Air Force and MDA schedule estimates. The concurrent F-15C and ALHK activities during the SDD phase minimum total time frames of between 8.5 or 9 years includes approximately 6 years to fully configure and integrate the first F-15C test bed platform. For both ALHK options the minimum SDD time frame estimates are driven by designing an 18 in. booster over an 8.5-yr time frame. However, the committee assumed, consistent with Air Force and MDA, that additional development time to complete an advanced KV extends the overall minimum SDD schedule by at least 6 months.

[d] The SDD range estimates unique to the F-15C airborne platform are for the cost of designing in airframe design modification for retrofitting at least two F-15Cs as flight test articles to accommodate the weapons carriage loads of each missile option, designing modifications to the fighter's existing stores management system, and the additional system design engineering required to accommodate, integrate, and test either the LITENING G4 or SNIPER surrogate pods on the two test bed fighters. The committee assumed the two F-15C fighters would be taken from the existing Air Force active fighter inventory or inactive (soon to be retired) drawdown fighter force.

Even though the committee for the sake of consistency went along with the Air Force/MDA briefing choice of the F-15C as the threshold airborne system baseline selected for the LCC estimates presented in this section, there may be a better mix of fighter choices for the Air Force and MDA to consider prior to beginning the SDD phase. Given the early stages of this development activity and the average age of over 25 years for the Air Force active duty inventory of 233 F-15C/Ds (see active duty inventory quantities for the F-15C/D and the average service life taken from "2010 USAF Almanac," *Air Force Magazine,* May 2010), the continuing investment in an F-15C service life extension program to sustain these retrofitted aging fighters may not provide the best return on investment over a 20-yr life cycle sustainment cost relative to the total LCC cost of using F-35A production fighters currently entering the USAF inventory. (In the Congressional Research Service (CRS) study by Jeremiah Gertler, "F-35 Joint Strike Fighter (JSF) Program: Background and Issues for Congress Report," CRS RL30563, September 23, 2010, the annual quantity of Air Force F-35As procured through FY 2010 was listed at 25, with a request for 23 more in FY 2011. At the time of the CRS report, past DOD plans increased the procurement for F-35As to a sustained rate of 80 aircraft per year, leading to a total procurement planned of 1,763 F-35As by around FY 2034.

[e] The SDD range estimate is the cost for the system engineering design, development, testing, and procurement of a sufficient quantity of either of the two ALHK interceptor missile options for DT and initial operational testing and evaluation (IOT&E) flight testing required on the two F-15C test bed aircraft.

[f] The maximum time frames listed for the cost-benefits study are consistent with the estimates specified in the Air Force and MDA briefing along with the SDD time frame of 3 years for the F-15C-unique development activities. However, owing to the uncertainty of the time frames for completing and fully testing a new 18-in. booster and integrating it with either an existing SM-3 Block IB or an advanced new design, the committee added another 1.5 years, or between 15 and 20 percent more time, as slack time for mitigating potential risks.

[g] The cost-benefit study was described in the Air Force/MDA briefing as an 18-month study, the funding for which (between $15 million and $30 million in FY 2010 dollars) was at the time of the briefing was pending joint approval.

[h] The Air Force and MDA identified the two development risk reduction items and potential "long-poles in the tent" relative to beginning the SDD phase for improving the technical maturity and demonstrating the capability of demonstrating airborne IR stereo ranging of ballistic missiles with two or more fighters flying in formation with the same sensor suite and airborne Link-16 communications package integrated with BMDS off-board sensor systems (e.g., the proposed ABIR transmitting cueing data on TOM updates to the ALHK booster via the onboard fire control unit prior to KV separation.

pod or a SNIPER surrogate pod would vary depending on the current onboard F-15C sensor suite configuration of each fighter before or shortly after the approval to begin production of the ALHK Interceptor missiles.

Table E-16 summarizes the total procurement cost range estimate of between $7.6 billion and $11.2 billion, made up of an estimated AUPC for both ALHK missile options of between $7 million and $8.3 million each and a range estimate for the average retrofit recurring cost per F-15C of between $6 million and approximately $29 million (all in FY 2010 dollars.).

TABLE E-16 ALHK Interceptor Program Procurement Cost Estimates (FY 2010 dollars)

ALHK Missile Option	Interceptor Quantity[a]	Missile AUPC (FY 2010 million $)[a]	F-15C Quantity[a]	Average Retrofit Cost per F-15C (FY 2010 million $)		Total Procurement Cost (FY 2010 billion $)	
				Minimum[a]	Maximum[b]	Minimum	Maximum
18-in. booster with SM-3 Block IB KV	1,000	7.0	100	6.0	24.8	7.6	9.5
18-in. booster with advanced KV	1,000	8.3	100	8.3	29.4	9.1	11.2

[a] For each of the two options, the committee assumed based the AUPC estimates on the same ALHK missile interceptor buy quantity of 1,000 and weight-based cost estimates as specified in the Air Force/MDA briefing. The

lower bound, or minimum, average recurring cost range estimates per fighter are based on, as needed, retrofitting and installing the latest LITENING or SNIPER targeting pods discussed above, associated modification kits and system testing for 100 F-15C fighters, which is the same quantity also previously specified by the Air Force and MDA study team. The lower bound or minimum average retrofit costs per F-15C are the same as the values stated in the Air Force/MDA briefing. The assumption the Air Force and MDA briefers made for the ALHK missiles interceptor study was that there would be up to 100 F-15C Air Force and Air National Guard fighters available. The Air Force and MDA average retrofit costs per F-15C are based on SPO estimates of platform and integration costs.

[b] The upper bound, or maximum, average retrofit cost per F-15C development cost for each option is based on an increased retrofit effort, where the estimates are based on the average relative cost percentage factor of 1.42 times the AUPC cost to account for the costs of fabrication for unique F-15C airframe interface electrical and mechanical hardware, installation and integration of targeting pods and the modification kits, and end-to-end system test and evaluation.

F-15Cs configured with the onboard sensor suite and configured with a weapons carriage capable of loading two ALHK missiles per fighter are assumed to begin incurring annual O&S costs the fiscal year when IOC is met, which the Air Force and MDA briefing defined when 50 interceptor missiles are produced in low-rate initial production (LRIP) and delivered to one designated fighter squadron along with at least five retrofitted combat-ready F-15Cs. FOC was defined as being achieved 7 years later, when delivery of the total quantity of 1,000 interceptors is phased into the inventory and all 100 retrofitted F-15Cs are in the fighter force and available for forward deployment to fighter squadrons.

The Air Force and MDA briefing estimated the O&S costs over a 15-yr period as the delta cost, or difference, between the sustainment costs of retrofitting F-15Cs and the cost of sustaining F-15Cs already in the Air Force active inventory. The O&S estimate based on marginal costs allows the combatant commanders (COCOMs) additional flexibility in using the retrofitted F-15C for other fighter missions.

System O&S Costs

When needed for the ballistic missile defense mission, the COCOM would forward deploy the F-15Cs in CAPs to attempt a boost, or early, intercept by ensuring the placement and continuous on-station coverage needed. The COCOMs can also be in the rear and deploy the retrofitted F-15Cs in CAPs closer to a defended area. In both cases, robust and timely communication links of sufficient bandwidth are necessary to transfer fire-quality tracks to and from the ALHK F-15C platform. In either CONOPS scenario, the ALHK interceptors can be used to execute limited boost-phase intercepts but will likely require as a prerequisite that the Air Force penetrate enemy airspace to gain air supremacy in advance of the deployment of these CAPs.

For purposes of arriving at O&S costs, the committee estimated the average marginal annual O&S costs on both a per fighter basis and a per CAP basis with three retrofitted F-16Cs each. It limited the O&S estimates to retrofitted F-15Cs for performing this ballistic missile defense mission. Using the above CONOPS and F-15Cs per CAP set of assumptions, the committee computed the average annual O&S delta cost over a steady-state period of 15 years for sustaining 100 F-15Cs in the active inventory at $425,000, which is the equivalent of 1.2 percent of the rough-order-of-magnitude (ROM) annual O&S estimate of $4.3 million for sustaining today’s Air Force fleet of F-15C/Ds (in FY 2010 dollars). Given the uncertainty in the CONOPS and varying percentage use of the force of retrofitted F-15Cs to perform ballistic missile tracking and intercept missions along with other fighter missions, the committee considered this a lower bound estimate of the marginal O&S cost of sustaining this fighter force as it operates these missions over a 20-yr service life. The marginal O&S estimate also does not include any most likely USAF investments in extending the service life of the F-15C airframe, engine, and other flight-critical equipment to continue operations from the start of the sustainment phase projected by the Air Force and MDA to begin in FY 2018 and continue for at least another 20 years to FY-2038.[28]

Table E-17 lists the minimum and maximum average marginal annual O&S cost per aircraft and per CAP, and total marginal O&S costs for 100 retrofitted multimission F-15Cs from IOC forward through FOC and continuing on over the 20-yr service life for sustaining.

TABLE E-17 Retrofitted F-15C Marginal O&S Cost Estimates (FY 2010 dollars)

	Average Marginal Annual O&S Costs		Total Marginal O&S Costs over 20-Yr Service Life
	Retrofitted F-15C (thousand $)	F-15C CAP (million $)	(million $)
Minimum	51	0.2	116
Maximum[a]	426	1.3	966

[a] The maximum marginal cost is based on an eightfold increase over the minimum average marginal annual O&S cost per retrofitted F-15C, which is equates to an increase in the marginal cost of up to 10 percent of the average annual cost of F-15C/Ds over the minimum estimate based on 1.2 percent.

Space-Based Interceptor Systems

Cost Overview and Analysis Approach of SBI Constellation

The committee investigated three options for an SBI system: a boost-phase system and a hybrid system capable of doing both boost-phase and midcourse intercept, and a satellite for midcourse intercept. The criterion for optimization was to minimize the total cost from initial R&D through a 20-yr LCC.

The first option was a satellite capable of intercepting both solid and liquid ICBMS with very low leakage, and the second could only achieve very low leakage against liquid ICBMs. For the second class, some geometric leakage for solid ICBMs would be expected, approximately 30 percent for 0-sec decision time and 60 percent for 30-sec decision time; the midcourse capability would be used to deal with the leakage. The third class was a constellation capable of midcourse intercepts only.

The design requirements for the KV were reviewed, with an eye toward minimizing the mass but preserving the functionality needed as well as using sound design principles and technologies that are robust and credible. For the hybrid system the committee slightly relaxed the divert requirement from 2.5 km/sec, used by the APS report to assure the ability to engage solids, to 2.0 km/sec. This reduction of divert velocity may degrade the ability to intercept solid ICBMs and their unanticipated acceleration, but the committee has not tried to quantify that loss. The saving in mass (and therefore cost) is substantial.

Three generic KVs were considered, one for each type of constellations. One was optimized for boost phase only, another was optimized to be able to do both boost phase and midcourse intercepts, and, finally, one was only for midcourse intercepts. The boost phase only KV has a divert velocity of 2.5 km/sec to be able to engage solids and 10-cm diameter optics.

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[28] A recent Aircraft Structural Integrity Program (ASIP) briefing by the Air Force from Warner Robbins AFB projected the service life and active duty of Air National Guard and Reserve inventory for providing air superiority missions of approximately 250 F-15Cs to extend out to the mid-2020s. (Joseph D. Lane, USAF-WR-ALC/GRM Eagle Division, and Paul A. Reid, Boeing, “Certifying the F-15C Beyond 2025,” Aircraft Structural Integrity Program (ASIP) 2010 Conference, presentation to the committee, December 2, 2010.)

The hybrid system has a divert velocity of 2.0 km/sec and 20-cm diameter optics. The midcourse only KV has a divert velocity of 0.6 km/sec and 20-cm diameter optics. For doing midcourse intercepts the committee chose 20-cm diameter optics rather than 30 cm as was used for ground-based interceptors because the long viewing is neither needed nor wanted for SBIs. First, the number of satellites is large, so no target will be far from one of them. The second reason has to do with the orbital mechanics. Once launched the SBI will likely have a very high velocity, perhaps even an escape velocity. A target 3,000 km away means that the KV would need to expend resources to go "around the corner" of Earth to reach the target.

For a given KV, a parametric search was made varying burnout velocity (v_{bo}). In this manner, the number of satellites was determined with the requirement of having at least two satellites within range of any single threat missile. The committee considered both one-stage and two-stage boosters but found that for the speeds needed, one-stage boosters are impractical. The associated LCC was computed as was the value of v_{bo}. In this way the number of satellites was found that minimized that cost.

LCC) included these:

- Development,
- Production,
- Life jacket mass computed at 50 percent of SBI (booster plus KV mass),
- Learning curve assumptions for the average unit cost of the SBI satellite as a function of the total production buy quantity,
- Average 7-yr SABI satellite on-orbit lifetime and two replacements launches over the 20 years of system sustainment,
- Launch costs, and
- Sustainment costs for operating and maintaining the constellation size and fixed number of SBI satellites on-orbit over a 20-yr period.

The committee evaluated five cases of constellations and estimated the minimum LCCs for the optimum SBI with $v_{bo} = 5$ km/sec. It required that, on average, at least two satellites be within range for an intercept:

Case 1. Boost-phase coverage of the entire United States with at least one satellite within range against both solid and liquid ICBMs. Decision time = 0 sec.

Case 2. Boost-phase coverage as in Case 1, except that the design only assures coverage against liquids, and midcourse capability is added.

Case 3. Same as Case 1, except decision time = 30 sec.

Case 4. Same as Case 2, except decision time = 30 sec.

Case 5. Only midcourse defense is offered.

Table E-18 summarizes the results of this optimization for the defense of the entire United States[29] and most of Canada against ICBM Launches from Iran or North Korea for decision times of td = 0 sec and 30 sec.

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[29] The entire United States means CONUS, Alaska, and Hawaii. "Most of Canada" means coverage over areas south of the northernmost part of Alaska.

TABLE E-18 Number of Satellites, Other Parameters, and LCC

Description	Optics Diameter (cm)	KV Mass (kg)	KV Divert km/sec	SBI Mass (kg)	N_{sat}	20-Yr LCC Cost (FY 2010 billion $) Minimum	Maximum
Decision time t_d = 0 sec							
Case 1: BPI solid + liquid BPI	10	164	2.5	1,978	1,000	296	500
Case 2: BPI liquid + midcourse	20	149	2.0	1,796	400	119	200
Decision time t_d = 30 sec							
Case 3: BPI solid + liquid	10	164	2.5	1,978	2,000	581	978
Case 4: BPI liquid + midcourse	20	149	2.0	1,796	650	187	311
Case 5: Midcourse only	20	81	0.6	977	200	43	73

Each of these SBIs needs a “garage” or a “life jacket” in orbit to provide housing and certain utilities. Table E-19 provides a representative list of the life-jacket hardware envisioned to fill these functions. The committee estimated the total mass of the life jacket to be approximately 50 percent of the total mass of the SBI including the KV.

TABLE E-19 SBI Life Jacket Subsystems and Hardware

- Propulsion
  - Hall effect ion engine and controls (apogee kick motor)
  - Propellant
- Structure and shielding (survivability housing) radiators
- Electrical Power
  - Solar panel power distribution unit
  - Batteries
  - DC-to-DC convertors (power convertor electronics)
- RF receiver and antenna (tracking telemetry and communications)
- Attitude determination and control
  - Momentum wheels and controller
  - Horizon/star tracker sensors
  - Low-rate attitude control system for momentum dump

Cost Trade-off Results of Varying SBI Booster Burnout Velocities

The committee took the KV of Cases 2, 3, and 4 and explored the 20-yr LCC as a function of v_{bo}.

Figure E-4 shows a plot of the two-stage mass, the total constellation mass, and the 20-yr LCC (average of the minimum and maximum values) as a function of v_{bo} of the interceptor. To do this it did the following: For each value of v_{bo} an appropriate SBI booster was chosen to achieve v_{bo} for the given payload. For each value of v_{bo} the number of satellites was computed to achieve the needed coverage. From the SBI mass, the associated life jacket mass, and the number of satellites placed in orbit, the total mass to orbit was computed. The LCC was computed using the methodology described below and plotted. The minimum is for v_{bo} between 4 and 5 km/sec. The committee chose 5 km/sec for all subsequent design work. Although the minimum of the curve is a little lower, 5 km/sec was chosen to provide a somewhat robust design in case more reach should be needed.

A major driver of the LCC is the cost of delivering the total mass of the constellation to orbit. To deploy a total SBI system constellation of this size and total mass would require large increase in the current annual U.S. launch capacity, the construction of additional launch pads and associated facilities, and major increases in the production rate of evolved extendable launch vehicle (EELV)-class and emerging next-generation smaller class of launch lift vehicles, such as the Falcon 9 family of Space X vehicles. From a launch lift readiness best-case perspective, EELV-class Delta IV H (heavy) launch vehicles could lift up to 14 SBI satellites (with life jackets) at a mass margin of around 15 percent to a 330-km altitude at an orbital inclination of between 45 and 55 degrees. Of course, this would be contingent upon being able to package all the satellites along with payload adaptors to fit within the volumetric limitations of the Delta IV's upper-stage shroud. Even if this rather optimistic assumption is technically feasible, it would still require as a best-case scenario a minimum of 115 launches to lift a constellation size of 1,000 SBI satellites. In a 2006 CBO Report on projections of U.S. launch capacity and demand through 2020, the minimum number of 115 SBI launches EELV-class heavy-lift launch vehicles needed is to be compared with the total annual capacity of 50 launches per year projected and is considerably greater than the total U.S. government and commercial annual demand of 25 to 30 launches per year projected for 2015 and beyond.[30]

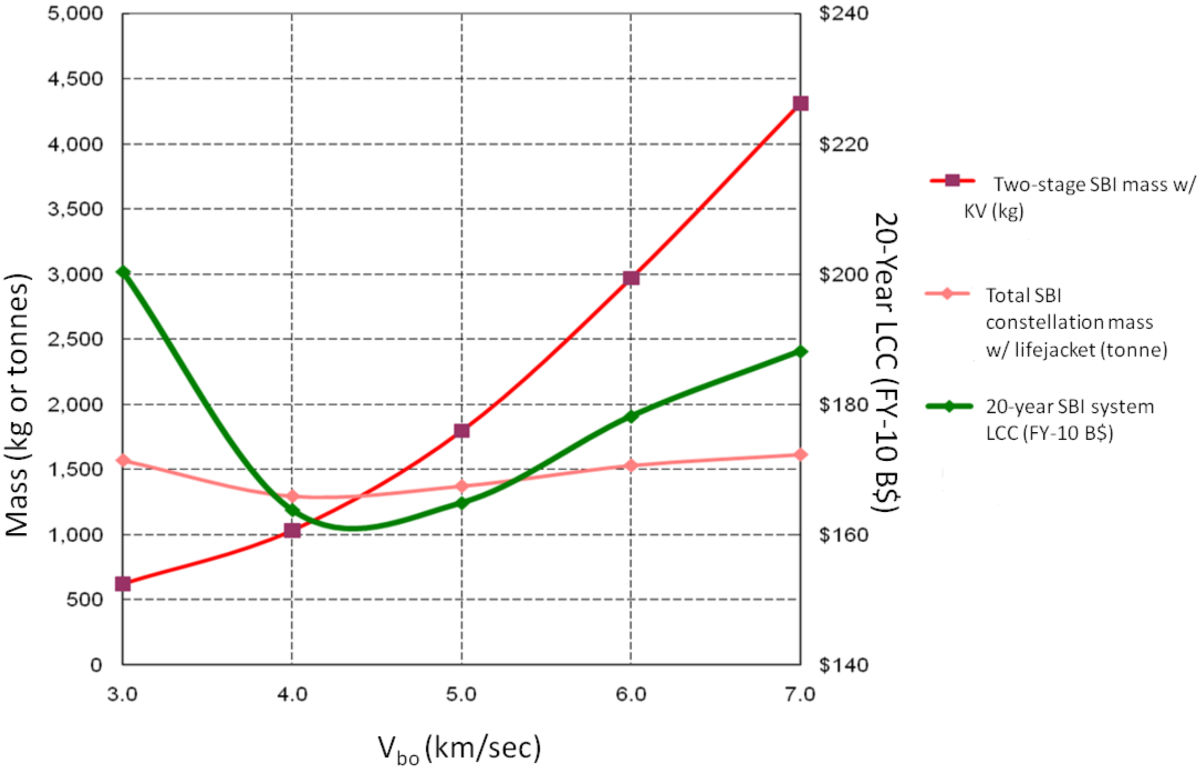

FIGURE E-4 Optimal booster burnout velocity at lowest LCC.

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[30] For further details see Figure 1-2, "Projections of U.S. Launch Capacity and Demand within the CBO Report," in Alternatives for Future U.S. Space-Launch Capabilities, Publication No. 2568, October 2006. CBO defined "capacity" as the number of launches that the infrastructure and production facilities can support if fully manned and funded. "Demand" is either the number of launches required on historical launch manifests or current projections of future launch manifests.

Case 1: SBI System for Boost-Phase Defense Missions

Here is an example of the kind of analysis that was done for the LCC estimates. Case 1 is an SBI constellation system designed for the boost-phase mission against both solid and liquid ICBMs with a two-stage booster having a v_{bo} = 5 km/sec, which has been sized to be capable of lifting a KV with a wet mass of approximately 164 kg. The wet mass of the KV is configured with the 10-cm optical diameter IR seeker. The DACS consists of four divert thrusters with the KV capable of a 2.5 km/sec divert velocity and sized for slightly reduced lower bound closing velocities of 8 km/sec to 14 km/sec. The maximum total time of the KV operation can also be extended up to 400 sec.

Table E-20 shows SBI system 20-yr LCC range estimates for acquiring and launching an SBI constellation of about 1,000 satellites and sustaining this fully operational capability over a 20-yr period. Key ground rules and assumptions contained in footnotes to this table, are consistently applied for this case as well as the other cases.

TABLE E-20 Case 1: SBI System 20-Yr LCCs (FY 2010 billion dollars)

Cost Element	Minimum/Low	Maximum/High
Research and development		
SBI booster	1.1	2.4
KV and seeker	1.1	2.3
Marginal C2BMC[a]	0.5	1.0
Life jacket	0.4	0.9
NRE I&T cost (30 percent)	0.9	2.0
Subtotal[b]	4.0	8.7
Production		
Two-stage booster[c]	10.6	14.4
Kill vehicle[d]	6.3	8.6
Seeker[e]	0.6	0.8
Life jacket	31.9	43.5
Integration and Test[f]	7.4	27.0
SBI satellites[g]	56.8	94.4
Launch services[h]	45.1	77.1
Subtotal	101.9	171.5
Operations (over 20 years)		
Satellite and mission operations	4.1	8.2
Replacement SBI satellites	113.6	188.7
Launch services[i]	72.9	123.4
Subtotal	190.6	320.3
Total	296.4	500.5

NOTE: Case 1 has v_{bo} = 5 km/sec, K_v divert = 2.5 km/sec, 10-cm optics on the KV, boost-phase liquids, 70 percent solids.

[a] The RDT&E costs include the marginal cost of designing the communications links and meeting the interface needs for integrating the on-orbit SBI satellite operations with the ballistic missile defense C2BMC. (The nonrecurring engineering marginal cost is based on taking the average C2BMC program budget from FY 2008 through FY-2015 as reported in the FY-2011 MDA PB, converting it to FY 2010 dollars, and spreading the average annual estimate over an assumed 4-yr development timeline.

[b] The RDT&E lower bound, or minimum, cost estimate consists of the nonrecurring system design and engineering minimum cost estimates for modifying a two-stage heritage booster assessed at 50 percent new design, along with a KV and IR seeker design and packaging of the subsystems and components of the life jacket, which the committee assessed as a relatively new design. (The assumptions and resulting estimates for the nonrecurring engineering efforts are based on best engineering judgment as to the current technical maturity or readiness level or assessed TRL value; the complexity of the design, and the extent to which the past program heritage can be leveraged for the two-stage booster, the KV (which includes both the DACs and IR seeker), and the life jacket.) It

also includes estimates of the manufacturing, assembly, integration and on-orbit testing costs of producing two sets of interceptors, KVs, and life jackets and launching two fully configured protoflight SBI satellites as part of the development phase. (The recurring cost of producing the two prototype SBI satellites is based on an assumed increase of 50 percent over the first unit, or T1, production cost estimate calculated as the basis for the procurement cost estimates. This step-back factor of 1.5 is based on a best engineering judgment assumption of higher first-time labor costs due to the inefficiencies of producing the hardware with a hands-on engineering compared to a more fully automated manufacturing environment and a higher one-time cost of buying the space-qualified parts needed only for the two prototypes.

To account for requirements creep, schedule changes and annual budget shift, the upper bound, or maximum, RDT&E estimate is 72 percent higher than the lower bound, minimum, estimate. This increase is based on the actual cost growth experienced on an analogous THAAD development program as reported in the most recent DOD Selected Acquisition Report for this system. (With 90 percent of the effort completed, the THAAD program's most recent Selected Acquisition Report of December 31, 2009, reported a contractor RDT&E estimated price at completion cost that had grown 57 percent since the initial contract award in August 2000. The contract called for delivering 50 THAAD interceptors and corresponding hardware for two U.S. Army batteries. In constant-year dollars, the corresponding RDT&E budget over this same time frame also increased by 72 percent.)

[c] The two-stage boost phase T1 unit cost is based on applying a weight-based linear regression cost estimate relationship generated using two analogous data points: the GBI OBV three-stage booster weight of 22,483 kg and an average unit cost of $47 million (FY 10 dollars) as the lower-bound value of $2.7 million per ton and the Aegis SM-2 Block IA missile (less the KV) weight of 1,436 kg and an average unit cost of $8.1 million per ton and an upper-bound value of $8.9 million per ton.

[d] The remainder of the KV unit cost estimates for the DACs, avionics, structure, tankage hardware, etc. is based on applying similar weight and other technical parameters as input values for the Air Force's latest edition of the Unmanned Spacecraft Cost Model (USCM). The committee also used the USCM primarily weight-based parametric model to estimate the life jacket for each of subsystems and components previously listed in Table E-19.

[e] The IR seeker unit production cost is based on technical parameter values of the optics diameter, focal plane array size and material, electronics weights, etc. as input to a commercial parametric cost model, SEER Electro-Optics.

[f] The projected uncertainty in the recurring SBI satellite integration and testing cost estimates is accounted for by applying a 15 percent factor to the sum of the recurring cost of the two-stage booster, the KV, the seeker, and the life jacket as the minimum estimate and a 30 percent factor for the maximum estimate.

[g] The SBI satellite production cost range estimates are based on computing the first unit, T1, production cost and then calculating the cumulative average unit costs based on learning curve or CIC slope values to account for manufacturing labor efficiencies and discounts on parts costs as a function of the quantity being produced. Since the projected labor efficiencies and material discounts are not fixed and could vary for producing IR seekers, DACs, avionics, and life jacket subsystems, the committee based the lower bound, or minimum, set of cost estimates on a steeper CIC slope, 95 percent, compared to an upper bound, or maximum, cost estimate based on a flatter slope, 98 percent.

[h] For launch services costs, the committee based the range estimates on the cost to launch a given mass to lower Earth orbit (LEO). It used this cost to calculate the cost of lifting the total SBI satellite constellation wet mass required to achieve FOC. The projections are based on the forecast for the current and emerging candidate set of U.S. launch vehicles available supply and the total U.S. military, NASA, and commercial space system industries' demand in the FY 2015 to FY 2020 time frame and again in the FY 2025 and beyond time frame for launching replacement SBI satellites after reaching FOC and continuing over the 20-yr life cycle period. The preceding section provides further details on the launch service cost and launch lift performance capabilities of the candidate set of U.S. boosters.

It should be noted that the launch service cost per mass to LEO is based on keeping within the total launch lift capability of the candidate launch vehicles that have been identified. This total launch mass estimated comprises the total wet mass of the multiple SBI satellites, the mass of the candidate launch vehicle's payload adaptor(s), and an acceptable launch mass margin.

However, it should also be noted that cost factors being applied are also contingent upon ensuring that the computed total launch lift mass also can be packaged in a stowed configuration to fit within the volumetric constraints of the upper-stage shroud of the candidate launch vehicle.

As part of the total acquisition cost to reach FOC, the committee set the minimum launch service cost at $13.0 million per ton in FY 2010 dollars based on a representative service cost of approximately $250 million per launch in FY 2010 dollars for an EELV Delta IV heavy vehicle with a maximum lift of approximately 19,240 kg to 330 km altitude at a 45 to 55 degree orbital inclination. (The launch services cost information for the EELV class of Delta IV heavy and medium boosters was extracted from Edgar Zapata, 2008, *A Review of Costs of US Evolved Expendable Launch Vehicles (EELV),* National Aeronautics and Space Administration, Kennedy Space Center, February 5. The specific launch performance information for the Delta IV heavy and medium class of vehicles was extracted from S.J. Isakowitz, J.B. Hopkins, and J.P. Hopkins, Jr., 2004, "International Reference Guide to Space Launch Systems," 4th ed., American Institute of Aeronautics and Astronautics.) The Delta IV Heavy is configured with a 5-m diameter fairing with two additional core common boosters as strap-on motors to the primary launch vehicle. The maximum launch service cost was set at $22.2 million per ton based on the same representative service cost of $250 million per launch for a Delta IV Medium + (5.4) vehicle with a maximum lift of approximately 11,250 kg to 330 km altitude at a 45 degree inclination. The Delta IV Medium launch vehicle is configured with a 5-m diameter fairing with four additional strap-on motors.

[i] After FOC, the committee set the launch cost per ton for SBI replacement launches in the 20-yr life cycle period at projected minimum and maximum values in the post FY 2025 time frame. The cost reflected slightly lower costs owing to the larger projected market supply of smaller launch vehicles, such as SpaceX Corporation's Falcon 9 boosters launched from several different U.S. sites. These would be viable candidates beyond the Delta IV and Atlas V expendable vehicles launched from Cape Canaveral and Vandenberg Air Force Base. (Cost and performance information for Falcon 9 was extracted from SpaceX, 2009, "Falcon 9 User's Guide," SCM 2009-010 Revision 1, Figure 4.1 Falcon 9 Block 2 Performance to Low Earth Orbit (Cape Canaveral). The committee set the minimum value at $10.4 million per ton, 20 percent lower than the previously stated value of $13.0 million per ton by assuming a proportional number of launches would be performed on the Falcon 9 family of vehicles where SpaceX Standard Launch Services cited a price (which includes additional 8 percent for re-flight insurance) for a booster with a maximum lift capability to LEO for approximately 7,200 kg of approximately $8.4 million per ton. The committee set the maximum value at $20.0 million per ton, or approximately 10 percent lower than the previously stated value of $22.2 million per ton. This value used a more conservative representative mix of Delta IV or Atlas V class vehicles, with Falcon 9 boosters as needed to keep up with SBI satellite replacement launch demands.

Other SBI System Case LCC Summaries

The summary tables for the LCC range estimates for Cases 2 through 5, which vary with respect to the number of satellites, are provided below as Tables E-21 through E-24.

Costs of Launching Space-Based Interceptors

As discussed in Appendix J, in the section Space-Based Interceptors," the required total wet mass of SBI satellites on orbit dominates the design considerations for any space system, largely because of the very high cost of deploying space systems mass into orbit.

History of Cited EELV Launch Costs Early in the history of the Air Force's EELV program the estimated average launch cost was based on an annual launch rate mission model of heavy lift boosters assuming 95 launches in the FY 2002 to FY 2022 time frame, which would have corresponded approximately to 5 or 6 launches per year, split evenly among the Atlas V and Delta IV family of boosters. In FY 2006, if one divided the RDT&E budget for EELV of $838 million by six, the average cost per launch was computed at approximately $150 million in FY 2010 dollars.[31] This FY 2006 budget is a 66 percent increase over previous years and reflects the "new acquisition strategy, which separated the launch price from the infrastructure or launch pad

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[31] The Air Force RDT&E-based estimated in *Forecast International,* a 2004 space systems market forecast had cited the Pentagon paying, on average, ~$171 million (in FY 2010 dollars) for each EELV based on a 117-unit buy. This cost will vary depending on the booster vehicle configuration. This estimate of ~$171 million included cost growth of 26 percent from FY 2004 to FY 2005 after approximately four Delta IVs and four Atlas Vs had been produced.

TABLE E-21 Case 2: SBI System 20-Yr LCC Results for 1,000 Satellites (FY 2010 billion dollars)

Cost Element	Minimum/Low	Maximum/High
Research and development		
SBI booster	1.1	2.4
KV and seeker	1.1	2.3
Marginal C2BMC	0.5	1.0
Life jacket	0.4	0.9
NRE I&T cost (30 percent)	0.9	2.0
Subtotal	4.0	8.7
Production		
Two-stage booster	10.6	14.4
Kill vehicle	6.3	8.6
Seeker	0.6	0.8
Life jacket	31.9	43.5
Integration and Test	7.4	27.0
SBI satellites	56.8	94.4
Launch services	45.1	77.1
Subtotal	101.9	171.5
Operations (over 20 years)		
Satellite and mission operations	4.1	8.2
Replacement SBI satellites	113.6	188.7
Launch services	72.9	123.4
Subtotal	190.6	320.3
Total	296.4	500.5

NOTE: Case 1 has v_{bo} = 5 km/sec, K_v divert = 2.5 km/sec, 10-cm optics on the KV, boost-phase liquids, 70 percent solids.

TABLE E-22 Case 3: SBI System 20-Yr LCC Results for 2,000 Satellites (FY 2010 billion dollars)

Cost Element	Minimum/Low	Maximum/High
Research and development		
SBI booster	1.1	2.4
KV and seeker	1.1	2.3
Marginal C2BMC	0.5	1.0
Life jacket	0.4	0.9
NRE I&T cost (30 percent)	0.9	2.0
Subtotal	4.0	8.7
Production		
Two-stage booster	21.0	28.7
Kill vehicle	12.5	17.1
Seeker	1.2	1.7
Life jacket	63.4	86.5
Integration and Test	14.7	53.6
SBI satellites	112.9	187.6
Launch services	90	153
Subtotal	202.6	340.9
Operations (over 20 years)		
Satellite and mission operations	4.1	8.2
Replacement SBI satellites	225.8	375.2
Launch services	144.8	245.3
Subtotal	374.8	628.7
Total	581.3	978.3

NOTE: Case 1 has v_{bo} = 5 km/sec, K_v divert = 2.5 km/sec, 10-cm optics on the KV, boost-phase liquids, 70 percent solids.

TABLE E-23 Case 4: SBI System 20-Yr LCC Results for 650 Satellites (FY 2010 billion dollars)

Cost Element	Minimum/Low	Maximum/High
Research and development		
SBI booster	1.1	2.3
KV and seeker	1.0	2.2
Marginal C2BMC	0.4	1.0
Life jacket	0.4	0.8
NRE I&T cost (30 percent)	0.9	1.9
Subtotal	4.0	8.1
Production		
Two-stage booster	1.4	1.8
Kill vehicle	0.9	1.1
Seeker	0.1	0.1
Life jacket	4.4	5.6
Integration and Test	1.0	3.5
SBI satellites	7.8	12.1
Launch services	4.7	8.0
Subtotal	12.5	20.1
Operations (over 20 years)		
Satellite and mission operations	4.1	8.2
Replacement SBI satellites	15.5	24.3
Launch services	7.6	12.8
Subtotal	27.2	45.3
Total	43.7	73.5

NOTE: Case 1 has v_{bo} = 5 km/sec, K_v divert = 2.0 km/sec, 20-cm optics on the KV, boost-phase liquids +midcourse.

TABLE E-24 Case 5: SBI System 20-Yr LCC Results for 200 Satellites (FY 2010 billion dollars)

Cost Element	Minimum/Low	Maximum/High
Research and development		
SBI booster	1.1	2.3
KV and seeker	1.1	2.2
Marginal C2BMC	0.5	1.0
Life jacket	0.4	0.8
NRE I&T cost (30 percent)	0.9	1.9
Subtotal	3.8	8.2
Production		
Two-stage booster	6.6	8.8
Kill vehicle	4.1	5.4
Seeker	0.4	0.6
Life jacket	20.4	27.0
Integration and Test	4.7	16.7
SBI satellites	36.2	58.4
Launch services	26.8	45.8
Subtotal	63.0	104.2
Operations (over 20 years)		
Satellite and mission operations	4.1	8.2
Replacement SBI satellites	72.5	116.7
Launch services	43.3	73.3
Subtotal	119.9	198.3
Total	186.7	310.7

NOTE: Case 1 has v_{bo} = 5 km/sec, K_v divert = 0.6 km/sec, 20-cm optics on the KV, mid course only.

and range costs. In that same fiscal year, the AF stated that Follow on Launch Service Buys will include launch service costs on a fixed price contract."

Another source, *Aviation Week and Space Technology* in the article "Rocket Boosters—To Prop Up Domestic Rocket Industry," stated that the Air Force had abandoned competition on April 18, 2005, and cited a higher FY 2006 budget request based on an average EELV launch and associated services cost estimate of approximately $183 million (in FY 2010 dollars), which was said to vary depending on the complexity of integrating the payload onto the rocket and the desired orbit. A more recent NASA launch service contract award with United Launch Alliance in March 2009 cited a cost of approximately $605 million (in FY 2010 dollars) for launching multiple space system payloads on four EELV boosters from their Science Mission and Space Operations Mission Directorates.[32] The average launch service cost of approximately $151 million is planned for 2011 through 2014, all of it for designated Atlas V launch vehicles. The total value of the award includes the costs of the rockets, "plus additional [launch services] under other contracts for payload processing; launch vehicle integration; and tracking, data and telemetry support."[33]

Launch Service Costs per Launch Lift Mass to Lower Earth Orbit The committee bounded the cost per launch lift mass to LEO using two different candidate EELV Delta IV configurations based on the computed SBI total mass launch lift performance values up to an altitude of approximately 330 km. It should be noted that the actual costs are likely to be higher due to recent cost increases for EELV.

An upper bound (or pessimistic) estimate of $15.5 million per ton (in FY 2010 dollars) was computed using the lower-end Delta IV Medium + (5.4) representative booster with a maximum lift capability of approximately 11,250 kg up to 330 km altitude at 45-degree inclination angle of performance and a representative launch service cost of approximately $148 million per launch in FY 2002 dollars or $174 million per launch in FY 2010 dollars. Figure E-5 illustrates the Delta IV Medium + (5.4) launch lift performance as a function of orbital altitude. The booster has a 5-m diameter fairing with four additional strap-on motors.

A lower bound (or optimistic) minimum estimate OF $9.8 million per ton (in FY 2010 dollars) was computed based on a representative cost of $160 million per launch (in FY 2002 dollars) or $188 million per launch in FY 2010 dollars for a Delta IV Heavy vehicle with a maximum lift of approximately 19,240 kg to 330 km altitude at a 45- to 55-degree orbital inclination performance.[34] Figure E-6 illustrates the Delta IV Heavy launch lift performance as a function of orbital altitude. The Delta IV Heavy is configured with a 5-m diameter fairing with two additional core common boosters as strap-on motors to the primary launch vehicle.

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[32] The launches will be from Launch Complex 41 at Cape Canaveral Air Force Station [in] Florida. The four payloads are the Radiation Belt Storm Probes mission [with a launch in 2011;] the Magnetospheric Multiscale mission [with a launch in 2014;] and the Tracking and Data Relay Satellites (TDRS) K and L (or TDRS-K and TDRS-L) missions [planned for a 2012 and 2013 launches, respectively.] See NASA contract release: C09-011, March 16, 2009.

[33] See NASA contract release: C09-011, March 16, 2009.

[34] The launch services cost and performance information for this Delta IV Heavy and Medium class of vehicles is from S.J. Isakowitz, J.B. Hopkins, J.P. Hopkins, Jr., 2004, International Reference Guide to Space Launch Systems, 4th edition, American Institute of Aeronautics and Astronautics.

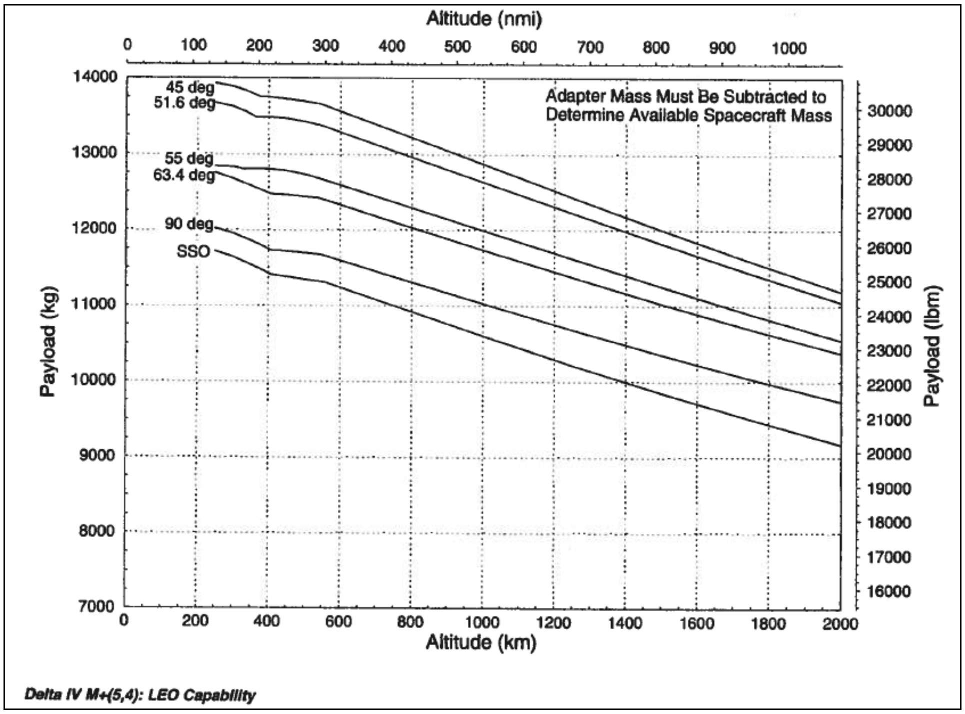

FIGURE E-5 Delta IV medium + (5.4) LEO launch lift capability. SOURCE: S.J. Isakowitz, J.B. Hopkins, J.P. Hopkins, Jr. 2004. International Reference Guide to Space Launch Systems, 4th edition, American Institute of Aeronautics and Astronautics.

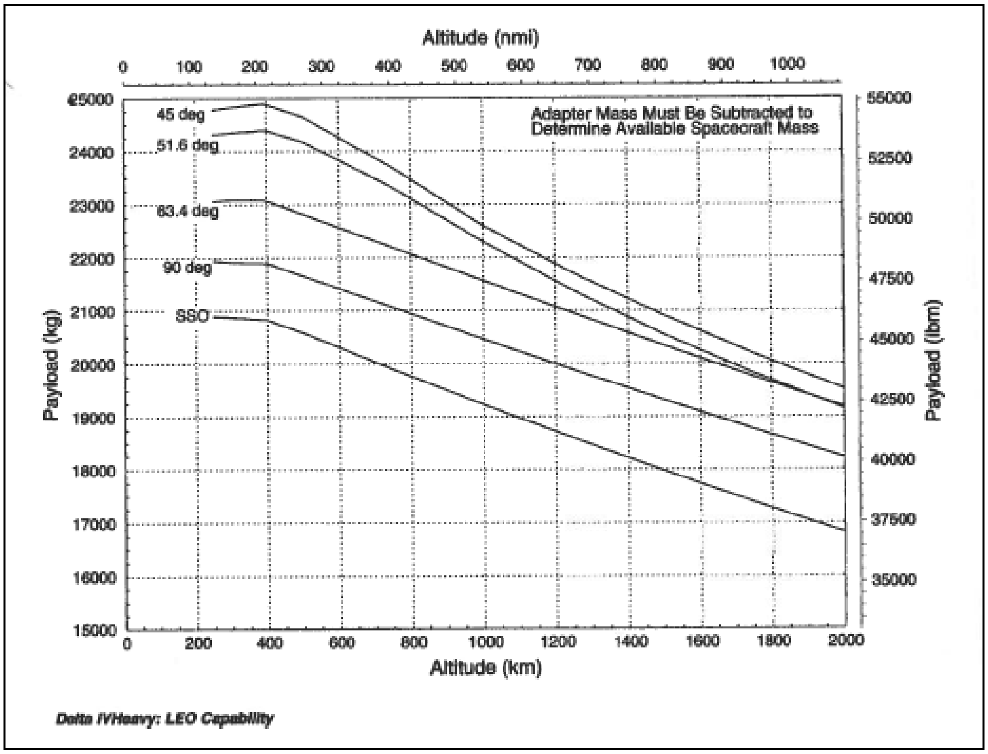

FIGURE E-6 Delta IV heavy LEO launch lift capability. SOURCE: S.J. Isakowitz, J.B. Hopkins, J.P. Hopkins, Jr. 2004. International Reference Guide to Space Launch Systems, 4th edition, American Institute of Aeronautics and Astronautics.

The minimum and maximum estimates of cost per total mass lift to LEO were used for computing launch service costs to attain FOC of the total number of SBI satellites required for the constellation. Once FOC is reached and assuming an average life of 7 years for each SBI satellite, replacement launches will be required after FY 2025.

Given the forecast increase in U.S. demand for space systems launch and the emerging use of launch sites other than Vandenberg Air Force Base and Cape Canaveral and use of classes of boosters other than EELVs, the committee reduced the minimum cost of total mass lift to LEO estimate based on the representative market price for launch services cited by SpaceX for the Falcon 9 Block 2 (see Figure E-7).[35]

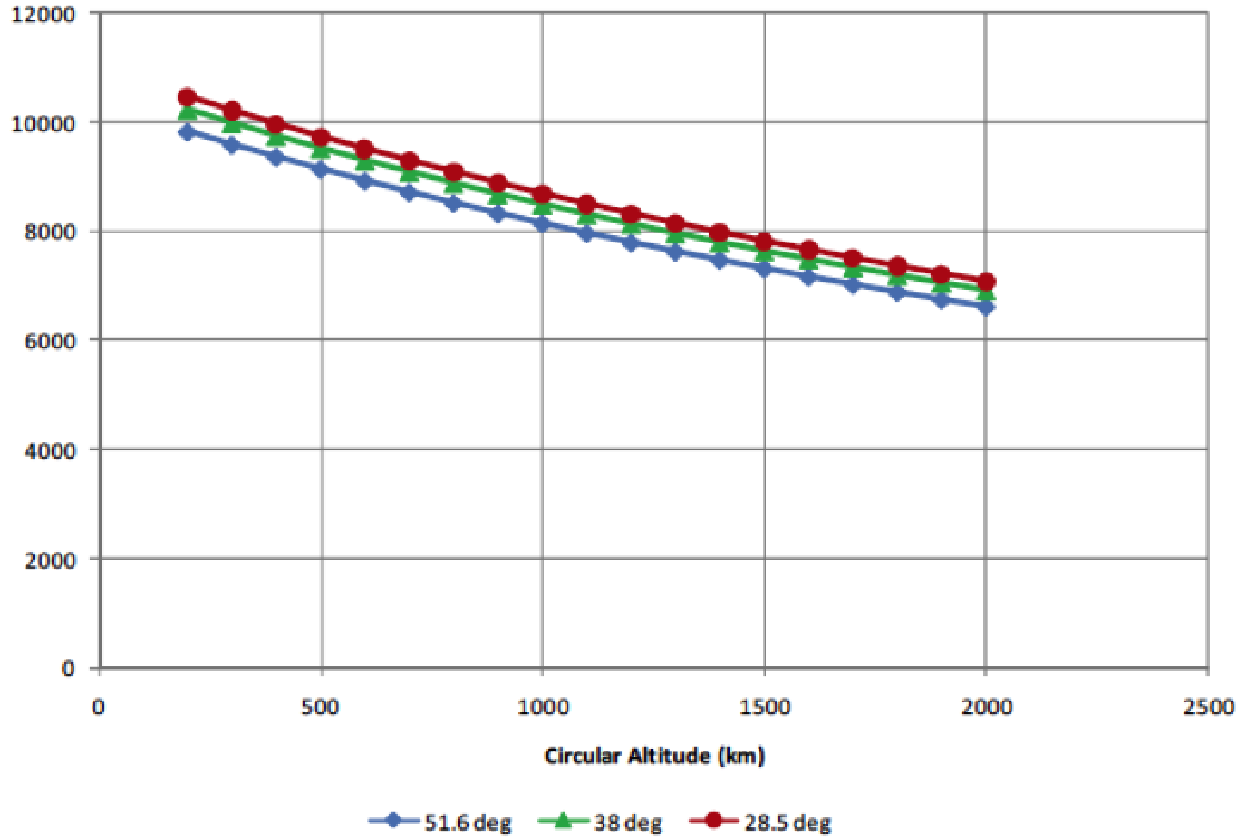

FIGURE E-7 Falcon 9 Block 2 LEO launch lift capability. SOURCE: Space X "Falcon 9 User's Guide," SCM 2009-010 Revision 1, Figure 4.1, "Falcon 9 Block 2 Performance to Low Earth Orbit (Cape Canaveral).

After FOC, the committee set the launch cost per ton for SBI replacement launches in the 20-yr life cycle period at the projected minimum and maximum values after FY 2025. These values reflected the larger market supply of smaller launch vehicles, such as SpaceX Corporation's Falcon 9 boosters launched from several different U.S. sites as viable candidates beyond the Delta IV and Atlas V expendable vehicles launched from Cape Canaveral and Vandenberg Air Force Base.

The minimum cost of $8.4 million per ton is based on the standard launch services prices for Falcon 9 and includes additional 8 percent for reflight insurance. It pertains to a booster with

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[35] Cost and performance information is from SpaceX, 2009, "Falcon 9 User's Guide, SCM 2009-010 Revision 1, Figure 4.1, "Falcon 9 Block 2 Performance to Low Earth Orbit (Cape Canaveral).

a maximum lift capability to LEO of approximately 7,200 kg after subtracting the mass estimated for the payload adaptor along with a 10 percent additional mass margin.[36]

In this post-FOC time frame, the maximum cost was set at $13.9 million per ton, or approximately 10 percent less than the previously stated value of $15.5 million per ton. This value is based on use of an assumed mix of Delta IV or Atlas V class vehicles and Falcon 9 boosters needed to keep up with SBI satellite replacement competitive launch demands.

SBI Constellation Cost and Affordability Observations

Space-based interceptors are a potentially attractive option for boost-phase intercept because they are not constrained by geography to being located close to the target missile. In addition, their accelerations and velocities are not constrained by the atmosphere, so in theory they could have longer reaches than surface- and air-based interceptors.

Those potential operational advantages are offset, however, by a number of drawbacks. First, placing mass into LEO is very expensive, $8.400 and $15,500 per kilogram (in FY 2010 dollars). This makes total launch lift mass the dominant design criterion for space-based systems. For example, mass constraints limit the ability to exploit the lack of atmosphere to increase the reach of the interceptors. In fact, the committee found that the total mass in orbit was minimized when accelerations and flyout velocities were less than those assumed in almost all of U.S. surface-based interceptors. Second, the orbital motion of the satellites and the rotation of Earth result in requirements for very large numbers of satellites to ensure that at least one would be close enough to intercept a single missile before it achieved enough velocity to deliver its munitions to the United States. This coverage requirement, in turn, results in constellations with masses that are between 650 and 2,000 SBI satellites.[37] The total launch lift mass to orbit of even the lower end of the constellation size calls for a significant effort and would require at least a threefold increase in the current launch capacity of the United States.

GMD Evolved CONUS-Based Systems

The GMD-E cost estimates were based on the committee's recommended interceptor baseline design that would be half the size and weight of the current GBI and should be designed to be either silo emplaced at a CONUS-based site in the Northeast or, as described in the next section, to be carried in a canister on a transporter/erector/launcher (TEL) at a prepositioned fixed site or sites in Europe.

The committee recommended that the additional site in CONUS should be activated in upstate New York or Maine. For both CONUS and forward-based GMD-E missiles, the new interceptor's KV should be designed around a 30-cm-diameter two color LWIR sensor with an additional visible band to detect targets as far away as 3,000 km. It is estimated that this sensor with a blow-down-cooled 256 × 256 three-color focal plane array cued by SBIRS high and/or

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[36] Cost and performance information was extracted from Space X "Falcon 9 User's Guide,, SCM 2009-010 Revision 1, Figure 4.1, "Falcon 9 Block 2 Performance to Low Earth Orbit (Cape Canaveral).

[37] The Case 1 SBI satellite constellation size of 1,000 for the boost-phase intercept mission should be considered optimistic against solid-propellant ICBMs. If more realistic geographical scenarios are considered, ICBMs would have to be intercepted sooner than 5 sec before burnout, resulting in an increase in the total number of interceptors and total system mass. For example, the number of interceptors and total mass would increase by about 25 percent if the constellation were designed to defend the United States against Iran. The effects of more realistic scenarios are less pronounced against liquid-propellant ICBMs, because they burn longer and accelerate more rapidly at the end of their burns.

forward-based X-band radars can observe the threat complex for as long as 300 sec with adequate and ever increasing signal-to-noise ratio. The committee estimates that a KV with the features described below will have a wet mass of 106-110 kg and a total divert capability of 600 m/sec. The GMD-E interceptor and KV must be designed to receive uplinks at any time during fly-out and to downlink what the KV sees any time after shroud removal without vehicle hardware or orientation constraints, preferably at X-band using one or more of the X-band radars that has the interceptor in view for both up- and downlinks. The KV should have a battery operating time in excess of 700 sec after boost, and the blow-down cooling should take the focal plane and immediately adjacent optical structure to 100 K when the sensor is uncapped. With the focal plane heat sunk, the sensor optics may warm up slowly from that point as the interceptor closes on the target complex. The KV should include an inflatable kill enhancement "net" similar to that used on ERIS to deal with any objects tethered close to the threat warhead.

One of the key assumptions driving the nonrecurring and recurring estimates for the CONUS-based GMD-E booster was leveraging the previous MDA Kinetic Energy Intercept (KEI) program and take advantage of relevant heritage designs and MDA's sunk investment cost of $5.1 billion (in FY-2010 dollars) expended on work performed under this now cancelled program of record.[38]

Our evolved GMD interceptor's proposed design would use a smaller two-stage interceptor with a total burn time less than a third that of the existing GBI carrying a larger more capable KV. It would also require adding a third missile field site in the U.S. Northeastern and a fourth site in the U.S. North Central states together with additional X- band radars to protect the eastern United States and Canada against Iranian threats.

The 20-yr LCC range estimates for this CONUS-based GMD-E system are summarized in Table E-25.

TABLE E-25 Estimated LCC for CONUS-Based GMD-E System Total (FY 2010 billion dollars)

	Minimum	Maximum
Development	3.3	4.7
Procurement	5.8	9.6
Force quantity buy	Two missile field sites 50 interceptors each (30 operational missiles + test assets)	
MILCON[a]	2.4	2.4
20-yr O&S	7.6	8.6
Total	19.1	25.3

[a] The LCC for a CONUS-based Evolved GMD system includes an estimate for the construction cost of Northeast and North Central missile fields and other infrastructure facilities at these two sites.

Forward-Based GMD-E Systems

As part of the committee's evaluation of the gain in effectiveness to defend against ballistic missile attacks from our allies within Europe and others, it estimated the 20-yr LCC of a forward-deployed, evolved GMD transportable interceptor system located in Poland as a hedging strategy alternative to the land-based SM-3 Block IIB interceptor previously described a previous section, "Aegis SM-3 Block IIB." The 20-yr LCC of a forward-based GMD-E interceptor system is provided below as Table E-26.

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[38] The booster configuration developed on the KEI program went through successful ground firing of the first-stage motor, and the second-stage motor was ready to fire just before the program was terminated in late 2009.

TABLE E-26 Estimated LCC for Forward-Based GMD-E System Total (FY 2010 dollars)

	Minimum	Maximum
Development	2.8	3.9
Procurement	1.6	2.3
Force quantity buy	One land-based site in Europe	
MILCON	None required	None required
20-yr O&S	2.0	3.0
Total	6.4	9.2

LIFE CYCLE COST DETAILS PROGRAMS OF RECORD SYSTEMS

GMD Systems

Relevant Systems Investment Costs

Table E-27 lists the GMD system total program investment costs (i.e., budget) expended through FY 2009 of approximately $34 billion (in FY 2010 constant dollars).[39] In the 1993 time frame, the primary mission of the boost interceptor and the NMD programs was to develop a defensive system that could “intercept incoming ballistic missile warheads outside Earth’s atmosphere [exoatmosphere] and destroy them by force of the impact.”[40] This mission and the programs that followed have since evolved, beginning with the GMD incremental block development of a midcourse interceptor system in 2002. During this 8-yr period from FY 2002 through FY 2009, the MDA total annual investment was approximately $22 billion, which in addition to program block development included the production of 40 three-stage GBI operational and test interceptors. The average annual investment for the GMD system and the BPI program during this time frame was approximately $2.7 billion.

TABLE E-27 GMD System Investment Costs Through FY 2009 (FY 2010 dollars)

Cost Element	Program Time Frame	Total Investment (billions)	Average Annual Investment (millions)
Boost-phase interceptor	1993-1999	1.4	227
NMD DEM/VAL	1995-2001	8.7	1,444
BMDS interceptor	2003-2009	1.9	265
GMD block development	2002-2009	21.7	2,716
Total investment		33.7	

NOTE: The total program acquisition (RDT&E and procurement) investment sunk costs for the current GMD system and previous predecessor system expended through FY 2009 are based on the sum of the fiscal year actuals reported from the FY 2012 MDA FYDP PB justification sheets submitted in February 2011 and on previous MDA (formerly BMDO) annual PB justification sheets. For the other interceptor and sensor systems, these same references cited are the basis for the other interceptor and sensor system sunk investment cost calculations, and where applicable, from the other military services listed in the tables in this appendix.

System Acquisition Costs

Table E-28 provides the AUPC estimates for the three-stage GBI of $70.2 million, which includes the EKV at close to $30 million, which is 42 percent of the total interceptor cost and also includes the booster avionics module and integration, assembly, and checkout costs per

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[39] For system comparison purposes, all the costs provided in this appendix, as well as in Appendix J, are normalized to FY 2010 constant dollar, using the base year FY 2010 OSD inflation rate index issued on December 11, 2009.

[40] See MDA, Ground-Based Midcourse Defense (GBD) Validation of Operational Concept (VOC), Chapter 2.0, December 12, 2002.

TABLE E-28 GMD Three-Stage GBI Average Unit Procurement Costs (FY 2010 million dollars)[a]

GBI Cost Element	AUPC	
EKV	29.8	
Boost stack	19.8	
Booster avionics modules	6.5	
Integration, assembly, test, and checkout	4.1	Next five GBIs[b]
Total cost	70.2	86.5

[a] MDA provided the total cost estimate for five GBIs, which it was assumed were in FY 2010 dollars. ("MDA Ground-Based Midcourse Defense Response to NAS Cost Questions," August 12, 2010.

[b] MDA also noted that the purchase of refurbishment parts and flight test rotation kits impacted many suppliers. As a result, the GMDS program allocated $81.8 million (in FY 2010 dollars) specifically to value added vendor preservation by procuring long-lead items for the next five GBIs. MDA allocated $86.5 million, an upper bound projected AUPC estimate for the next five GBIs, in the budget evenly across this next production buy.

system. With regard to the EKV and in addition to the procurement of new three-stage GBIs, the FY 2011 MDA FYDP PB listed a separate procurement of the capability enhancement-II (CE-2) EKVs at a higher average unit cost of $39 million (also in FY 2010 dollars) for a quantity buy of seven. The enhanced EKV addresses the parts "obsolescence issues and provides additional processor throughput to support systemwide [advanced] discrimination capabilities."[41]

For forward projections of additional quantities of three-stage GBIs beyond the budget committed in the FY 2011 FYDP, the committee assumed the AUPC estimate of $70.2 million as a realistic lower bound estimate along with an upper bound estimate of $86.5 million.

System O&S Costs

Table E-29 lists the average annual sustainment or total operating and support costs for the GMD system at $290 million (in FY 2010 dollars) located at both FGA and VAFB.[42] MDA is currently pursuing "a competitive development and sustainment contract (DSC) for future development; fielding; test[ing]; systems engineering, integration and configuration management; equipment manufacturing and refurbishment; training; and operations and sustainment support for the GMD system and associated support facilities."[43] Specifically, the sustainment portion of the contract includes base operations maintenance support costs, which includes (1) "monitoring, diagnostics, and maintenance of fielded ground-based midcourse defense components," (2) "continued development and validation of maintenance procedures," (3) "tracking of repair parts stock levels," and (4) performing maintenance on a 24/7/365 basis at VAFB, FGA, and the MDIOC.[44] Sustainment costs are also for upgrading and maintaining the security system at FGA and "developing a competitive logistics acquisition strategy for follow-

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[41] See MDA, FY-2011 FYDP Research, Development, Test & Evaluation, President's Budget, Exhibit R-2, RDT&E Budget Item Justification, BA 4: Advanced Component Development & Prototypes (ACD&P), PE 0603882C: Ballistic Missile Defense Mid-Course Segment, February 2010.

[42] Until FY 2008, GMD BPI program RDT&E annual budgets from FY 2002 thru FY 2007 included a mix of sustainment or operations and support efforts as part of total costs, which were not separately identified within specific program element line item numbers and/or block development projects.

[43] See MDA, FY-2011 FYDP Research, Development, Test & Evaluation, President's Budget, Exhibit R-2, RDT&E Budget Item Justification, BA 4: Advanced Component Development & Prototypes (ACD&P), PE 0603882C: Ballistic Missile Defense Mid-Course Segment, February 2010.

[44] Ibid.

TABLE E-29 GMD System Average Annual O&S Cost (FY 2010 million dollars)

O&S Cost Elements	Average Annual O&S Cost FY 2010 through FY 2015	Distribution by Cost Element (%) MDA	Contractor	Army
Unit level manpower	53	0	21	79
Unit operations	4	0	0	100
Maintenance	59	0	100	0
Sustaining support	153	37	61	2
Indirect support	20	100	0	0
Total	290	26	57	17

NOTE: The annual O&S costs for the GMD program were provided by MDA in then-year dollars from FY 2010 through FY 2027 across the OSD CAPE cost elements. Also listed is a percentage breakdown by cost element and total O&S costs of the portion of MDA funds for sustaining and indirect support, MDA contractor funds from its RDT&E budget and Army funds for unit-level manpower and unit operations. An average was taken over the FY 2011 FYDP through FY 2015, and the average annual costs are expressed in FY 2010 constant year dollars.
SOURCE: "MDA Ground-Based Midcourse Defense Response to NAS Cost Questions," August 12, 2010.

on maintenance."[45] The average annual GMD O&S cost for a GBI force of 30 operational missiles is approximately $9.7 million per year (in constant FY 2010 dollars).

System Life Cycle Costs

From FY 2010 forward, the GMD system LCC range estimates for development, procurement, and 20-yr O&S are listed in Table E-30. The total estimate from FY 2010 forward of approximately $19.3 billion includes the following:

TABLE E-30 GMD System Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	10.6	14.5
Procurement	10.6	14.5
Force quantity buy[b]	12 GBIs	
MILCON[c]	1.10	1.10
20-yr O&S[d]	5.8	5.8
Total	16.4	20.3

[a] The FY 2012 MDA GMD system program RDT&E budget for development and procurement was not broken down by MDA. The total acquisition cost range estimate listed above consists of the total requested funds from FY 2010 through FY 2016 of $6.8 billion plus costs projected forward for the (1) minimum estimate for another 4 years through FY 2020 of $3.9 billion and (2) maximum estimate for another 8 years through FY 2024 of $7.7 billion based on the same average projected annual budget level of $965 million as the FY 2012 FYDP.

[b] In the FY 2012 FYDP PB, MDA requested budget for the interceptor force quantity buy from FY 2010 forward through FY 2016 of 12, which consists of one upgraded and fielded GBI and eleven new GBIs (numbers 34 through 44).

[c] The funds for the actual construction of the 14 silos and related facilities for Missile Field 2 are listed under the MDA FY-12 FYDP PB MILCON budget.

[d] The total O&S cost over a 20-yr service life is based on an average annual sustainment costs for the GMD system estimated at $290 million (in FY-2010 dollars) for the missile fields, silos and interceptors located at both Ft. Greely and VAFB.

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[45] See MDA, FY-2011 FYDP Research, Development, Test & Evaluation, President's Budget, Exhibit R-2, RDT&E Budget Item Justification, BA 4: Advanced Component Development & Prototypes (ACD&P), PE 0603882C: Ballistic Missile Defense Mid-Course Segment, February 2010.

- The requested funding for the MDA FY 2012 FYDP PB RDT&E budget for the GMD program of $6.8 billion (excluding sustainment funds) from FY 2010 through FY 2016 to procure additional three-stage boosters configured with enhanced KVs for completing the buildup and retrofit of existing interceptors to an objective operational force of 30 GBIs. In addition, the $6.7 billion budget includes funds for the procurement of launch site components (i.e., silos and silo interface vaults), launch support systems (e.g., command launch equipment), in-flight interceptor communications system data terminals, a communications network, an external systems interface, test exercisers, fire controls, and so on for Missile Field 2 at FGA.
- The sustainment funding for the missile fields, silos, command and control operations, and maintenance for ensuring 30 operationally available interceptors and additional test interceptors will be in place at both FGA and VAFB.

Aegis SM-3 Systems

Since both the SM-3 Block IIA codevelopment and SM-3 Block IIB or Aegis Ashore programs are relatively new programs of record that were covered earlier, this section is limited to providing a summary of the total Navy and MDA Aegis system investment costs through FY 2009, the average unit procurement costs of SM-3 Blocks IA and IB, and a discussion of projected sustainment costs of these ship-based missiles.

Relevant System Investment Costs

Table E-31 lists the total investment cost of approximately $17 billion and the average annual investment costs for earlier and current BMD Aegis programs from FY 1964 through FY 2009. The table includes program investments beginning with the initial Navy-funded investments (shaded rows) in the Aegis Weapon System program consisting of both the development of the SM-2 (RIM-66C) missile and the AN/SPY-1A radar beginning in FY 1964 and continuing forward with SM-2 Block I through IV program development efforts through FY 2002. (This table also includes Aegis BMD software development costs.) In parallel, originally BMDO and now MDA continued parallel program investments in initially developing sea-based and Navy theater area ballistic missiles beginning in FY 1993, followed by the procurement of SM-2 Blocks IV and V interceptors as well as vertical launch system (VLS) canisters in the FY 1999 through FY 2001 time frame.

TABLE E-31Aegis System Investment Costs Through FY 2009 (FY 2010 dollars)

Cost Element	Program Time Frame	Total Investment (billions)	Average Annual Investment (millions)
Navy Aegis Weapon System (RIM-66C SM-2 and AN/SPY-1A)	1964-1985	2.5	115
Navy Aegis SM-2 Blocks I to IV	1987-2002	1.2	140
Sea-based Navy theater area TBMD DEM/VAL and EMD	1993-2002	6.2	686
SM-2 Blocks IVA and V and VLS canisters procurement	1999-2001	0.3	93
BMD Aegis block development	2002-2009	6.9	865
BMD Aegis procurement	2009	0.1	103
Total Navy and MDA investment		16.9	

The next-generation SM-3 program was initiated in FY 2002 with the BMD Aegis block development program, which continues through the FY 2012 FYDP along with the parallel procurement of the first 71 SM-3 Block I A interceptors manufactured using MDA RDT&E funds beginning in FY-2009. According to the MDA FY 2012 FYDP budget, 61 of these interceptors are expected in the inventory by the end of FY 2010. The first 34 SM-3 Block IB interceptors are currently being produced using MDA RDT&E funds beginning in FY 2011.

System Acquisition Costs

From FY 2010 through FY 2016, the BMD Aegis RDT&E budget of approximately $7.5 billion continues, with the incremental development of Block 3.6.1 for the PAA Phase 1 midcourse and terminal layer defense and of Block 4.0.1 for improved radar tracking accuracy and RF discrimination, an improved SM-3 Block IB kinetic warhead, a Block 5.0 Aegis modernization program, a Block 5.0.1 improved terminal defense capability, and other activities.

As reported in the MDA FY 2011 FYDP budget, Table E-32 provides the cumulative AUPC estimate of $9.6 million for SM-3 Block IA interceptors based on a total quantity of 41 manufactured over two recent annual production lots, where FY 2009 costs are based on actual budget expenditures and FY 2010 on approved budgets. SM-3 Block IA production is scheduled to be completed around the second quarter of FY 2012.

Table E-32 also lists the cumulative AUPC estimate of $9.3 million for each SM-3 Block 1B based on a total buy quantity of 290 produced over the annual lot quantities listed below beginning with 8 in FY 2011, followed by 66 in FY 2012 and continuing on at 72 a year from FY 2013 through FY 2015. Further details on the computed cost improvement, or learning curve calculations, for SM-3 Block IB missile production are provided in the final main section.

TABLE E-32 Aegis SM-3 Average Unit Procurement Costs (FY 2010 million dollars)

	Cumulative Average Unit Cost	Total Quantity	Fiscal Year	Annual Lot Quantities	Average Unit Cost per Lot
SM-3 Block IA	9.6	41	FY 2009	23	9.3
(last two lots)			FY2010	18	10.0
SM-3 Block IB	9.3	290	FY 2011	8	11.6
			FY 2012	66	10.3
			FY 2013	72	9.4
			FY 2014	72	8.8
			FY 2015	72	8.5

NOTE: As stated, the costs listed came from the MDA FY 2011 FDYP budget details. (DOD, 2010, Department of Defense Fiscal Year (FY) 2011 President's Budget Missile Defense Agency Justification Book, Volume 2c, Research, Development, Test & Evaluation, Defense-Wide–0400,) The committee elected to use these costs rather than the data provided by MDA in the “AB Cost Estimates Supporting MDA Cost,” presentation to the committee, March 1, 2010, because the latter lacked the AUPC estimates by annual lot production quantity to allow comparison with the other missile systems.

System O&S Costs

With regard to Aegis BMD system O&S costs, MDA and the “Aegis BMD [program] negotiated agreements with the U.S. Navy for the [operation] and maintenance of BMD systems onboard U.S. Navy ships."[46] In the fall of 2005, the U.S. Navy (IWS3A) and the MDA BMD Aegis program office signed a memorandum of understanding (MOU) that established an O&S cost share for the sustainment of SM-3 Block IA missiles and the AWS BMD 3.6.1 Aegis ships, with the U.S. Navy being responsible for supplying funds for unit-level operations and indirect support personnel, contractor logistics support, support equipment, and staffing as the lead service project office.

MDA's portion of the O&S cost share is currently based on support efforts leveraged off existing contracts and infrastructure. In the FY 2011 FYDP budget, MDA specifically requested SM-3 missile sustainment funds of $64 million (in FY 2010 dollars) for O&S activities providing the U.S. Navy with (1) "in-service engineering support," (2) "[operations] and maintenance training for Aegis BMD ship crews," (3) "logistics support including technical manuals, spares," etc., (4) "reliability, maintainability and availability" (RM&A) analyses products, (5) "leadership and engineering/technical support to conduct Aegis Combat Systems Assessments," and (6) responses "to fleet issues related to Aegis BMD installations, BMD operations and BMD [emergent] events."[47] In addition, the MDA BMD Aegis program office provided the committee with a set of annual O&S cost estimates from FY 2010 through FY 2015 for the SM-3 Block IA and the AWS BMD Block 3.6.1 systems and the SM-3 Block IB and AWS BMD 4.0.1 systems.

The MDA BMD Aegis program office provided a set of annual O&S costs from FY 2010 through FY 2015 similar to its GMD GBI O&S cost element breakdown.[48] Table E-33 lists the total average annual O&S cost estimates for the SM-3 Block IA and AWS BMD 3.6.1 combination, which over that time frame represents the sustainment, on average, of 40 missiles and related AWS sustainment of 14 Aegis.[49] Since the BMD Aegis schedule as of November 2009 displayed full-rate production for SM-3 Block IB missiles continuing through the middle of FY 2013, the committee elected to compute the average annual O&S costs for this SM-3 block of missiles and corresponding AWS BMD 4.0.1 Aegis ship assets beginning in FY 2013 through FY 2015 under more fully deployed steady-state conditions. Table E-33 also lists the average annual O&S cost estimates for SM-3 Block IB and AWS BMD 4.0.1 systems, which is based on the same MDA sustainment roles and responsibilities as the previous SM-3 Block IA missiles and AWS BMD 3.6.1 systems. Based on this same premise, the average annual O&S costs over the FY 2103 through FY 2015 time frame represent MDA's sustainment of 102 Block IB missiles and 12 Aegis ships.[50]

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[46] See MDA, FY-2011 FYDP Research, Development, Test & Evaluation, President's Budget, Exhibit R-2, RDT&E Budget Item Justification, BA 4: Advanced Component Development & Prototypes (ACD&P), PE 0603882C: Ballistic Missile Defense Mid-Course Segment, February 2010.

[47] Ibid.

[48] MDA, "AB Cost Estimates Supporting MDA Cost," presentation to the committee, March 1, 2010.

[49] The cost per missile and per ship is based on the Aegis program office estimate of the average MDA O&S cost per SM-3 Block IB missile of approximately $0.25 million per year. The average MDA O&S cost per ship for AWS BMD 3.6.1 of approximately $0.60 million per year does not include the cost of this AWS block installation, checkout, and testing on the Aegis ships which was completed before FY 2010 .

[50] The average annual O&S cost per Aegis ship for this AWS Block upgrade is significantly higher than that for previous block upgrades since it also includes the integration, checkout, and testing on the ships concurrent with the deployment of SM-3 Block IB missiles.

TABLE E-33 Aegis SM-3 System Average Annual O&S Cost (FY 2010 million dollars)[a]

O&S Cost Elements	FY 2010 Through FY 2015 Average
SM-3 Block IA	
Initial spares	1.7
Engineering support	1.5
Missile surveillance	1.0
Recertification	4.4
PHS&T[b]	0.3
Fleet/RM&A support[c]	0.3
Transportation	0.1
Software	0.7
Total	9.9
AWS BMD 3.6.1	
AWS upgrades	7.3
Training	1.3
Total	8.6
SM-3 Block IB	
Initial spares	20.2
Engineering support	1.8
Missile surveillance	1.2
PHS&T[b]	0.3
Fleet/RM&A support[c]	0.3
Transportation	0.8
Software	0.8
Total	25.5
AWS BMD 4.0.1	
Test ship under way	14.0
AWS upgrades	47.3
LRS&T equipment	5.4
Engage equipment	5.4
Total	72.0

NOTE: The average annual cost of SM-3 Block IA and AWS BMD 3.6.1 is for FY 2010 through FY 2015 and that of SM-3 Block IB and AWS BMD 4.0.1 is for FY 2013 through FY 2015.

[a] Since an MOU is not currently in place for the SM-3 Block 1B missiles and AWS BMD 4.0.1 assets for Aegis ships, the MDA program office based the estimates for these two tables on the assumption that the U.S. Navy will agree to the same sustainment roles and responsibilities and an O&S cost share similar to that for SM-3 Block IA and AWS BMD 3.6.1. Since low rate initial production for the SM-3 Block IB missiles is currently under way, this set of O&S costs were reported at an 80 percent level of confidence .

[b] PHS&T, packaging, handling, shipping and transporting, the SM-3 missiles.

[c] RM&A, reliability, maintainability and availability.

THAAD Systems

Relevant System Investment Costs

The THAAD system investment began with BMDO funding a demonstration and validation (DEM/VAL) program beginning in FY 1992 and continued through an engineering, manufacturing, and development (EMD) through FY 2003 for the missile system, which includes the tactical support group (TSG), launcher, and ground-based radar. Table E-34 lists the total annual investment of over $16 billion in the THAAD system from FY 1992 through FY 2009. This investment includes the average annual investment over the first two phases of the development program through preplanned product improvement of $872 million over this initial 12-yr time frame, followed by the MDA THAAD block development program continuing through the next 6 years from FY 2004 through FY 2009 at an annual investment of over $1.1 billion per year, which is approximately 25 percent higher.

TABLE E-34 THAAD System Investment Costs Through FY-2009 (FY 2010 dollars)

	Program Time Frame	Total Investment (billions)	Average Annual Investment (millions)
DEM/VAL EMD (included ground-based radar)	1992-2003	9.6	872
Block development	2004-2009	6.7	1,123
Procurement	2009	0.1	106
Total investment		16.4	

System Acquisition Costs

According to the MDA FY 2012 FYDP PB, the THAAD program is continuing block development and concurrently expending procurement funds first initiated in FY 2009 for LRIP. Even though the first 50 THAAD interceptors were produced using RDT&E funds, the average missile unit costs are based on reported annual procurement budgets and lot quantity buys beginning in FY-2010 and continuing at the rate of between 65 and 68 per year from FY 2011 through FY 2016.

Table E-35 displays THAAD system AUPC costs for the missiles of $11.2 million based on a total production quantity of for 431, for launchers of $6.7 million based on a total quantity of 60, and for TFCC Tactical Support Groups (TSGs) of $10.7 million based on a total quantity of 18. The missile AUPC estimates provided by the MDA Director of Estimating (DOE) THAAD cost team assume that there will be no production breaks, no design changes, no unforeseen cost overruns, and no cost, technical, or schedule problems during full-rate production.[51] For the THAAD missile, the MDA DOE THAAD cost team assumed a learning curve of 93 percent. This is consistent with the committee's detailed calculations of the computed cost improvement, or learning curve calculations, for the THAAD missile production that are provided in the section "THAAD."

TABLE E-35 THAAD Average Unit Procurement Costs (FY 2010 million dollars)

	Cumulative Average Unit Cost	Total Quantity
THAAD interceptor	11.2	431
Launcher	6.7	60
TSG	10.7	18

The estimates for the launcher and TFCC TSG units are fixed-price estimates with no cost improvement or learning curve savings over the quantity produced. According to the MDA FY 2011 FYDP budget, TSG average unit costs are based on a production rate of four per year from FY 2013 through FY 2015. The average cost for procuring a THAAD battery, without the AN/TPY-2 terminal mode radar, ranges from a current estimate of $695 million to a projected $530 million with the continued interceptor lot buys through the FY 2015 time frame.

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[51] MDA. 2010. "DOE Cost Estimates Supporting NAS: THAAD Cost Team," February 26. Due to the delay in the start of production, these quantities are slightly higher than the total procurement quantities of 427 missiles, 54 launchers, and 15 TSGs requested in the MDA FY 2012 FYDP PB through FY 2016.

System O&S Costs

According to the MDA FY 2011 FYDP budget details, sustainment funds are for providing THAAD batteries with the "logistical support to field, operate, maintain, repair and replenish the THAAD weapon system as it [is] fielded to the Army. [It includes funds for] contractor logistics support (CLS) technicians responsible for field and sustainment maintenance, including the repair and supply chain management of the required spares and repair parts."[52] The specific CLS annual cost for the THAAD radar software maintenance for implementing the software maintenance plan required for postdeployment software sustainment (PDSS) is covered later in this appendix in the section after next, "AN/TPY-2 Radar Systems," as part of the average O&S cost estimate for the AN/TPY-2 radar.[53]

Table E-36 summarizes the THAAD system total annual O&S costs with subtotals reflecting the MDA and assumed U.S. Army projected shares as an average estimate over the FY 2010 through FY 2015 time frame. The table also breaks out the subtotals by O&S cost element.

TABLE E-36 THAAD System Average Annual O&S Cost (FY 2010 million dollars)

Cost Element	FY 2010 Through FY 2015 Average Annual O&S Cost
Sustaining support[a]	20.5
GFE and support equipment modification kits replacement[b]	1.3
Logistics support[c]	17.0
Phase adaptive approach[d]	93.3
MDA subtotal	132.1
Petroleum, oil, and lubricants[e]	0.8
GFE spares, repair parts, depot maintenance[f]	13.4
Indirect support[g]	7.8
Military personnel[h]	45.9
Army subtotal (see NOTE)	68.0
Total	200.0

NOTE: The total annual O&S cost estimates and the breakdown by cost elements were provided by the MDA DOE THAAD cost team from FY 2010 through FY 2015. (See MDA, DOE THAAD Cost Team, "DOE Cost Estimates," presentation to the committee, February 26, 2010. A separate discussion of the AN/TPY-2 forward-based radar recurring unit cost and annual O&S costs was discussed in Appendix I.). The average annual cost in FY 2010 dollars is summarized by O&S cost elements for both MDA and the assumed U.S. Army portion of the sustainment not covered under the MDA FY 2011 FYDP budget for the program element for the BMD terminal defense segment. The sustaining support cost element covers the annual O&S estimate for the interceptor, TFCC and launcher. The O&S costs assume that the full complement of 48 interceptors, 6 launchers, and 2 TFCC units needed for fielding a total of 9 THAAD batteries will be fully deployed by FY 2015. The estimates are based on the MDA DOE THAAD cost team's projections for this fiscal year. The total average O&S cost per year is approximately $38.7 million per year (in FY 2010 dollars), which does not include the O&S cost for the AN/TPY-2 terminal mode radar. The GFE and support equipment modification kits replacement costs cover the TFCC and launcher.

[a] Sustaining support costs cover the interceptor; TFCC and launcher and weapon system engineering; integrated logistics support; system testing; and program management.

[b] The cost of GFE, support equipment, and modification kit replacements covers TFCC and the launcher.

[c] Logistics support costs cover the interceptor, TFCC, and the launcher.

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[52] See MDA, FY-2011 FYDP Research, Development, Test & Evaluation, President's Budget, Exhibit R-2, RDT&E Budget Item Justification, BA 4: Advanced Component Development & Prototypes (ACD&P), PE 0603882C: Ballistic Missile Defense Mid-Course Segment, February 2010.

[53] In the THAAD FY 2010 sustainment plans, Lockheed-Martin provides 100 percent of the CLS responsible for fielding two battery systems and sustaining maintenance of all the hardware. Raytheon provides the CLS for the AN/TYP-2 radar and associated PPU.

[d] The MDA DOE THAAD cost team added this cost element for the Phased Adaptive Approach (PAA) even though the funds were not defined in its briefing to the committee. This PAA cost element was also not separately identified in funded elements reported in the MDA FY 2011 FYDP budget under the program element for the BMD terminal defense segment for THAAD.

[e] U.S. Army POL cost estimates are for the ground vehicles transporting the TFCC, launcher, and THAAD battery common and peculiar equipment.

[f] U.S. Army O&S cost estimates are for procuring GFE, spares, repair, and parts for performing depot maintenance for the TFCC and the launcher.

[g] U.S. Army indirect support costs are for sustainment of the entire THAAD battery suite of equipment, except for the AN/TPY-2 radar and PPUs.

[h] U.S. Army military personnel costs are for operating and maintaining the entire THAAD battery suite of equipment except for the AN/TPY-2 radar and the PPU.

System Life Cycle Costs

From FY-2010 forward, the THAAD system LCC range estimates for development, procurement, and 20-yr O&S costs, between $14 billion and $16 billion are listed in Table E-37. The total estimate from FY 2010 forward includes the following:

- The requested funding for FY 2012 FYDP PB from FY 2010 through FY 2016 for the THAAD development program, at approximately $2.5 billion, and the procurement program, at $5.2 billion, to procure 427 additional THAAD interceptors, launchers, and TSG workstations by FY 2016.
- The sustainment funding for operating and maintaining nine THAAD batteries over a 20-yr service life.

Consistent with the MDA FY 2011 and FY 2012 FYDP PB funding, the development and procurement cost estimates for AN/TPY-2 terminal mode radars for the THAAD systems as well as the THAAD battery O&S costs for sustaining these radars over 20 years are not included here; they are, however, covered separately later in this appendix (see Table E-42).

TABLE E-37 THAAD System Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	4.0	5.4
Procurement[b]	5.8	6.6
Force quantity buy[c]	471 missiles	527 missiles
MILCON	None required	None required
20-yr O&S[d]	4.0	4.0
Total	13.8	16.0

[a] The THAAD development cost range estimate of $4.0 billion to $5.4 billion is based on projecting the FY 2012 MDA THAAD system development total requested funds from FY 2010 through FY 2016, $2.5 billion, forward through the FY 2020 to FY 2024 time frame at the same continued annual average expenditure rate of approximately $360 million for at least 4 more and up to 8 moret years. The additional MDA (and possibly Army) RDT&E funding is assumed to continue block development improvements and the sustaining engineering necessary until nine fully configured and operational THAAD batteries are in place and the total operations, support, and material sustainment role is fully transitioned over to the Army.

[b] The THAAD procurement cost range estimate of approximately $5.8 billion up to $6.6 billion is based on the FY 2012 MDA THAAD system program procurement total requested funds from FY 2010 through FY 2016 of $5.3 billion and $0.5 billion to $1.3 billion of additional funds after FY 2016 for funding the procurement of at least 44 and at most of 100 additional THAAD missiles plus 6 launchers, 2 TSG workstations and any additional peculiar support equipment and other hardware necessary to fully configure nine Army batteries.

[c] The total force buy quantity of between 461 and 527 THAAD missiles will cover the total operational quantity needed for fully configuring nine Army batteries and the expendable assets to cover THAAD missile flight tests and operational readiness training exercises necessary from FY 2011 through the FY 2016 time frame.

[d] The committee estimated the THAAD system O&S annual average cost at $200 million (in FY 2010 dollars). The cost consists of both the MDA and Army portions for sustaining and fielding nine deployed batteries with each battery fully configured with 48 interceptors, 6 launchers, and 2 TFCC units.

PAC-3 Systems

Relevant System Investment Costs

Table E-38 summarizes the total DOD and Army investment of close to $16 billion from FY 1983 through FY 2009 beginning with the PAC-3 development program and continuing forward for 21 years to FY 2003 at an average investment of $183 million per year. Since FY 2004, the investment in PAC-3 was and still is primarily the responsibility of the Army (highlighted in green), including the commitment of procurement funding for producing a total of 975 missiles through FY 2009. The Army's LRIP of PAC-3 missiles began in the fourth quarter of FY 1999, and the first unit was delivered in September 2001.[54] The system IOT&E was completed by September 2002, and IOC was declared in June 2004. IOC was achieved when the first Patriiot operational battalion was fully equipped with five FUs and 32 PAC-3 missiles per FU. By the end of FY 2003, 268 missiles had been produced, and after that the Army procured another 707 missiles through FY 2009.

TABLE E-38 PAC-3 System Investment Costs Through FY 2009 (FY 2010 dollars)

	Program Time Frame	Total Investment (billions)	Average Annual Investment (millions)
PAC-3 RDT&E (defense-wide)	1983-2003	3.8	183
Army PAC-3 RDT&E	2004-2005	0.2	122
Army PAC-3 procurement (quantity = 975)	1997-2009	9.0	696
Army PAC-3 modifications	2000 (est.)-2009	2.8	282
Total DOD and Army investment		15.74	

System Acquisition Costs

Table E-39 provides both the PAC-3 missile cumulative average AUPC costs estimated at $3.1 million based on the MDA FY 2012 FYDP budget for a total quantity of 225 missiles, and the annual lot quantities from FY 2010 through FY 2012. In the Army FY 2012 RDT&E PB, there is a total budget of $366 million from FY 2011 through FY 2016 for development of a missile system enhancement (MSE) upgraded PAC-3 missile. The Army plans to procure 294 upgraded PAC-3 missiles from FY 2013 through FY 2016 at a total estimated cost of $2.1 billion and to buy another 1,234 MSE missiles after FY 2014 for a total inventory quantity of 1,528 missiles.

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[54] Most of the PAC-3 historical information was based on the Army's Patriot PAC-3 Dec-09 Selected Acquisition Report (SAR) and Army FY-11 RDT&E and Procurement Budget submitted in February 2010.

TABLE E-39 PAC-3 Missile Average Unit Procurement Costs (FY 2010 million dollars)

	Cumulative Average Unit Cost	Total Quantity	Fiscal Year	Annual Lot Quantities	Average Unit Cost per Lot
PAC-3 missile	3.13	225	FY 2010	59	3.42
			FY 2011	78	3.11
			FY 2012	88	2.94

Table E-40 lists the PAC-3 Battalion AUPC estimates for each of the main equipment hardware elements listed for each Army battery fire unit.[55] The Patriot battery fire unit total AUPC range estimate includes support equipment; the lower bound of approximately $237 million represents the total of the hardware element unit costs and the upper bound of $260.5 million includes a 10 percent contingency cost along with the costs provided to the committee by the Army.[56]

TABLE E-40 PAC-3 Battery Fire Unit Equipment AUPC (FY 2010 million $)

FU Equipment	Average Unit Cost	Quantity per Battery
Radar system	103.0	1
Engagement control station	26.8	1
Antenna mast group	10.5	1
Battery command post	7.5	1
PAC-3 launching station	7.4	6
Enhanced launcher electronic system (ELES)	5.4	6
Electrical power plant	3.1	1
Others	0.6	6
FU support equipment	7.3	1
Total battery cost (less PAC-3 missiles)	236.8-260.5	

System Life Cycle Costs

From FY 2010 forward, the Army PAC-3/MSE system LCC range estimates for development, procurement, and 20-yr O&S costs of approximately $14 billion to $16 billion are presented in Table E-41. The total estimate from FY 2010 forward includes the following:

- The requested Army funding for FY 2012 FYDP RDT&E PB of $0.4 billion for upgraded PAC-3 MSE development program, and the total Procurement budget requested of approximately $5.4 billion for the remaining procurement of another 275 PAC-3 missiles through FY 2012 ($1.5 billion); PAC-3 modifications ($1.4 billion), and 292 new PAC-3 MSE upgraded missiles and other hardware ($2.1 billion), the latter two programs over this FY 2010 through FY 2016 7-yr time frame.
- The sustainment funding for operating and maintaining the entire force of PAC-3/MSE batteries over a 20-yr service life.

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[55] "Patriot Battery/Battalion Life Cycle Cost provided to NAS," U.S. Army Air and Missiles Defense Lower Tier Project Office Program Executive Office.

[56] Ibid.

TABLE E-41 Army PAC-3/MSE System Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	0.36	0.44
Procurement[b]	11.5	16.9
Force quantity buy	275 new PAC-3 + 1,528 MSE missiles (and PAC-3 modifications)	
MILCON	None required	None required
20-yr O&S[c]	14.7	16.2
Total 20-yr LCC estimate	26.7	33.5

[a] The PAC-3/MSE development cost estimate of $0.4 billion is based on the FY 2012 Army RDT&E budget requested for the upgraded PAC-3 MSE system, approximately $366 million from FY 2011 through FY 2016.

[b] The PAC-3/MSE total procurement cost range estimate of between $11.5 billion and $16.9 billion comprises funding for three programs. The estimate is based on the FY 2012 Army missile procurement total requested from FY 2010 through FY 2016 of approximately $5.3 billion for another 275 PAC-2 missiles, 294 new MSE missiles, and annual PAC-3 procurement modification funds over this 7-yr time frame. The procurement cost also includes the projected cost of completing the Army's planned procurement of another 1,234 MSE missiles at an estimated total cost of between $5.6 and $8.9 billion. The lower bound, or minimum cost estimate, is based on the Army's cited budget to complete the production run (in FY 2010 dollars), with an assumed learning, or cost improvement, curve savings based on an average annual lot buy of 80 missiles. The upper bound, or maximum cost, estimate is based on applying the same allocated average procurement unit cost per missile for the first 294 MSE missiles projected forward over the remaining buy of 1,234 missiles at the same lot buy rate of 80 missiles per year. Finally, the procurement cost range estimate also includes funds for continuing the PAC-3 procurement modification kits beyond FY 2016 time frame. The lower bound, or minimum cost, was based on the Army's cited procurement budget to completion of over $0.8 billion. As an upper bound, the committee estimated the total PAC-3 procurement modification costs at approximately $3.0 billion, based on continuing to provide annual funds at the same level as the requested Army FY 2012 FYDP funding through FY 2016 of approximately $200 million, projected forward for another 15 years through the end of the MSE production of 1,234 missiles through FY 2030.

[c] Given a total force quantity of up to 1,500 PAC-3 missiles and another 1,528 MSE missiles, the total PAC-3/MSE system 20-yr O&S cost of between $14.7 and $16.2 billion for operating and maintaining one fully configured Army Patriot battalion consisting of four dedicated PAC-3/MSE batteries and a complement of launchers, radars, fire control units, and other hardware is based on an estimated average annual O&S cost for one Patriot battery at between $183.8 million and $202.1 million and one Patriot battalion at between $735.1 million and $808.6 million. These two sets of range estimates were provided to the committee by the Program Executive Office of the Army Air and Missiles Defense Lower Tier Project Office. The sustainment cost also covers operations and maintenance training, support services, spares and GFE of all the major system hardware elements and equipment.

AN/TPY-2 Radar Systems

Relevant System Investment Costs

Even though development costs for an earlier version of THAAD radars may have been initiated before FY 2003, it was elected to track and aggregate MDA investments in development costs for the AN/TPY-2 radar beginning in this fiscal year, FY 2011, with the BMDS radar block effort of 2006 and use of the TPS-X radar as a test bed for designing a forward-deployable radar with modified software algorithms for tracking and discrimination. In FY 2003, this radar block development was concurrent with the THAAD block design of 2004 and development of an interceptor against short- to medium-range ballistic missiles and asymmetric threats and demonstrations of exo- and high endoatmospheric intercept capability against a limited target set.

A transportable version of the forward-deployable X-band radars (FBX-T) was designed and deployed at VAFB and in Japan through FY 2006. During FY 2006, the FBX-T and THAAD radars were both designated as AN/TPY-2 radars. Block 2006 consists of an AN/TPY-2 basic program to develop releases of the software that allow searching and tracking in a forward-based role and to incorporate discrimination algorithms from Project Hercules.[57] The funds also covered development of other radar software and the use of modeling and simulation, hardware-in-the-loop testing, and validation of algorithms with the TPS-X radar at the Pacific Missile Range Facility.

Through the end of FY 2009, two more radar block development efforts were under way. Block 2008 focused on delivering updated software with new releases that were common to support AN/TPY-2 forward-based and THAAD radar missions and on the design of a mechanical steering kit to provide the AN/TPY-2 with real-time slewing in both azimuth and elevation. Block 2010 development focused on (1) upgrading the software based on discrimination database enhancements and (2) continuing to support the two radar missions.

Table E-42 summarizes the total MDA investments of $2.3 billion in AN/TPY-2 radar block developments and procurements as well as radar test and evaluations with SBX radars from FY 2003 through FY 2009.

TABLE E-42 AN/TPY-2 Radar System Investment Costs Through FY 2009 (FY 2010 dollars)

	Program Time Frame	Total Investment (billions)	Average Annual Investment (millions)
AN/TPY radar block development[a]	2003-2009	0.8	118
AN/TPY-2 procurement[b]	2003-2009	1.4	353
SBX and AN/TPY-2 radar test and evaluation[c]	2008-2009	0.1	49
Total investment		2.3	

[a] Even though MDA estimated for the committee sunk costs of $630 million (in FY 2010 dollars) associated with the AN/TPY-2 radar system development, these estimates only covered flight testing and BMDS ground testing. (The information is from MDA "TPY-2 Cost Estimate Supporting MDA Cost Presentations to National Academy of Sciences (NAS)," presentation to the committee, February 24, 2010.) As a result, the committee elected to base historical development costs during this time frame on a higher estimate of $828 million (in FY 2010 dollars) based on funds extracted from MDA FY 2004 through FY 2010 RDT&E budget justification sheets for the BMDS sensor program. These efforts focused on radar block developments described above and modeling and simulation, as well as ground and flight tests and evaluations.

[b] From FY 2003 through the end of FY 2009, six currently designated AN/TPY-2 radar systems have been produced and fielded, with a seventh system in production and expected to have been delivered in FY 2010. The procurement cost estimate listed above was provided as a sunk cost by MDA and represents the production cost estimate for AN/TPY-2 systems prior to FY 2010. (The MDA production cost estimate is relatively consistent with the magnitude of funds reported in the MDA FY 2003 through FY 2010 RDT&E budget justification sheets for the BMDS sensor program for this radar system's production, site activation and deployment, and system refurbishment costs.)

[c] Beginning in FY 2008 as part of the BMDS sensor program budget an effort was initiated for the joint testing and evaluation activities for both the AN/TPY-2 and the sea-based X-band radar (SBX) systems. This effort continues through FY 2015 using funds allocated and listed above.

System Acquisition Costs

MDA also provided the committee in February 2010 with an AUPC estimate for the AN/TPY-2 radar system of $210.8 million.[58] However, since the MDA FY 2012 FYDP PB was

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[57] Project Hercules funding was covered as part of MDA's Advanced Technology program and continued through FY 2010. It focused on developing algorithms and software in the context of persistent sensor coverage, pervasive weapons coverage, global battle management, effective targeting, and improved effectiveness in advanced environments.

[58] Missile Defense Agency Fiscal Year (FY) 2012 Budget Estimates, Procurement Defense-Wide, BMDS AN/TPY-2 Radars Procurement, Exhibit P-40, Budget Item Justification, February 2011.

released, the committee elected to use the lower AUPC estimate for the procurement of 11 AN/TPY-2 radar systems costing $179 million based on the annual budget for one in FY 2010 and two per year from FY 2012 through FY 2016.

System O&S Costs

For TM-configured radars, the MDA annual average O&S cost per system varies from a minimum of $14.9 million per system for two systems to be fielded in FY 2011 to a maximum of $20.7 million per system projected for three operational systems in the FY 2012 to FY 2013 time frame. However, MDA stated that these sustainment cost estimates do not include THAAD site-specific support costs or the annual Army military personnel, security, and base operations costs, which are included as part of the THAAD system sustainment costs.

Therefore in order to get a more complete set of support cost estimates for the TM-configured AN/TPY-2 radar, the committee included and computed radar-specific average annual O&S cost estimates per system based on the FY 2010 through FY 2015 annual costs provided by the MDA THAAD project office for the following sustainment activities funded specifically for AN/TPY-2 radar:[59]

- Sustaining and logistics support,[60]
- Repair of GFE and support equipment and procurement of replacement modifications for fielded radar systems, and
- Army-funded procurement of addition GFE, replenishment spares and repair parts, and depot maintenance.

The average annual O&S cost for these cost elements over these 6 years is $22.7 million. The average annual cost per THAAD TM radar varies from a minimum additional cost of $5.0 million per year for five radars fielded in FY 2014 to a maximum additional cost of $11.0 million per year for two radars fielded in FY 2011 (all in FY 2010 dollars).

Finally, the committee included an allocated annual O&S cost for the Army-funded indirect support and military personnel costs portion of the THAAD interceptor system cost for sustaining the fielded TM-configured radar. The average annual O&S cost for these elements over these 6 years is $5.5 million. The average annual cost per THAAD TM radar varies from a minimum additional cost of $1.4 million per year for five radars fielded in FY 2014 to a maximum additional cost of $2.7 million per year for two radars fielded in FY 2011 (all in FY 2010 dollars).

In summary, the total annual O&S cost per TM-configured AN/TPY-2 radar varies from a minimum cost of $21.3 million per system to a maximum of $34.4 million per system (in FY 2010 dollars).

System Life Cycle Costs

From FY 2010 forward, the AN/TPY-2 radar system LCC range estimates for continuing X-band radar incremental development, the planned procurement of 11 systems through FY

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[59] MDA. 2010. "DOE Cost Estimates Supporting NAS: THAAD Cost Team," February 26.

[60] In the THAAD FY-10 Sustainment Plans, Raytheon provided 100 percent of the contractor logistics support (CLS) maintenance of fielded AN/TYP-2 radars. Raytheon under the CLS contract is responsible for engineering support and radar software maintenance services.

2016, and 20-yr O&S costs of sustaining these forward-based radars is approximately $18 billion to $24 billion Table E-43). The total estimate from FY 2010 forward includes the following:

- The requested funding for FY 2012 FYDP PB from FY 2010 through FY 2016 for the BMD radar development program at approximately $4.0 billion and the AN/TPY-2 procurement program at $2.0 billion for 11 additional AN/TPY-2 radar systems through FY 2016.
- The sustainment funding for operating and maintaining these 11 forward-based X-band radars over a 20-yr service life.

TABLE E-43 AN/TPY-2 Radar System Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	4.0	5.7
Procurement[b]	2.0	2.0
Force quantity buy	11	11
MILCON	None required	None required
20-yr O&S[c]	12.1	16.6
Total 20-yr LCC estimate	18.1	24.3

[a] The AN/TPY-2 development cost range estimate of $4.0 billion to $5.7 billion includes the FY 2012 MDA BMD radar block development requested budget (excluding FY 2010 sustainment funds) from FY 2010 through FY-2016 of $2.4 billion for transitioning the Block 2010 AN/TPY-2 development into an X-band basic effort for continuing the incremental releases of software algorithms (CX-1 and CX-2). These releases are for improving discrimination and enhancing the common software that supports AN/TPY-2 radar operations worldwide. The effort also included the development of critical engagement conditions and empirical measurement events where data are obtained from ground and flight tests as input to system models and simulations.

Since procurement and delivery of the radar planned radar in FY 2012 FYDP time frame will not occur until after FY 2016, the committee estimated an upper bound, or maximum, cost estimate to account for continuing X-band development activities at least through the end of FY 2020 time frame. The additional cost of $1.7 billion is based on the projecting the same average annual funding, approximately $340 million, forward for another 5 years.

[b] The AN/TPY-2 radar system procurement cost estimate is based on the budget MDA requested in the FY 2012 FYDP PB of $2.0 billion, for 11 additional systems from FY 2010 through FY 2016 time frame.

[c] The total O&S cost for sustaining 11 AN/TPY-2 radar systems over a 20-yr service life is based on all the radars operating in a stand-alone, forward-based, mode. The lower bound, or minimum, O&S cost estimated is based on the annual cost for three FBM-configured systems fielded in FY 2011 at $54.8 million per system, and the maximum estimate is based on $75.4 million per system for two FBM-configured operational systems fielded in FY 2010. (As part of the Phase Adaptive Approach for the European missile defense system, MDA has proposed that each interceptor site location include a forward-based (FBM) AN/TPY-2 X-band radar system. The current estimate cited by MDA and used in a recent CBO report cited a projected annual sustainment cost of $70 million to operate this configured radar system in FY 2013. This projected annual O&S cost in constant FY 2010 dollars is comparable with the committee’s MDA-based maximum estimate of $75.4 million per system. However it should be noted that CBO increased the previously estimated MDA operations costs by 50 percent to account for the possible growth of these costs.

GBX (Stacked AN/TPY-2 Array) Radar System

The recommended Ground-Based Midcourse Defense-Evolved (GMD-E) deployment described in Chapter 5 takes advantage of the space-based SBIRS and DSP satellite systems, as well as currently planned forward-based AN/TPY-2 radars, referred to as standalone X-band radar (FBX), located in Japan and at one or more locations north of Iran.

As also described in Chapter 5, the recommended GMD-E provides a significant enhancement in land-based radars through the introduction of a recommended doubling of existing AN/TPY-2 radars, one stacked on top of the other. For the purposes of this report, the recommended doubled AN/TPY-2 radars are designated as GBX radars, and they would be deployed at fixed sites co-located with the UEWR (ballistic missile early warning system (BMEWS)) radars (Cape Cod, Massachusetts; Grand Forks, North Dakota; Thule, Greenland; and Fylingales, United Kingdom). Additionally, as a result of its analysis, the committee recommended in Chapter 5 that a fifth GBX radar be added at Clear, Alaska, and that the sea-based X-band (SBX) radar be moved permanently to Adak, Alaska.

Each GBX radar consists essentially of two non-mobile AN/TPY-2 radar systems with the two arrays mounted one above the other in a rigid assembly, coherently integrating the beam forming transmit and receive functions in the electronics and software. These double (or stacked) radars would be mounted on azimuth turntables (like the SBX radar) that could be mechanically reoriented (not scanned) through an azimuth sector of ~ 270 degrees.

Since the GBX utilizes existing proven designs and hardware with a now well defined cost basis, it takes advantage of the learning curve, especially on the transmit/receive (T/R) modules that represent a significant cost of each radar.

A summary of the 20-year life cycle costs (LCC) for the five GBX radars is provided in Table E-44 for acquiring and sustaining the system at the five sites noted above and in Chapter 5.

TABLE E-44 GBX Radar System Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development	0.8	1.0
Procurement	1.6	1.6
Force quantity buy	5	5
MILCON	0.1	0.2
20-yr O&S	5.5	7.5
Total 20-yr LCC estimate	8.0	10.3

Note: These estimates do not include flight test costs as they are covered as separate line items for ongoing system validation in MDA’s budget.

The costing used for the GBX radar is based on AN/TPY-2 and SBX radar cost data. The development cost estimate covers the development and validation of electronics and software modifications and the fixed mount and turntable based on SBX radar estimates. The unit cost for the turntable and installation are derived from estimated cost of the SBX radar turntable. The GBX radar is configured to provide double the power of the AN/TPY-2 radar and includes an FBX network communication package. All tractor/trailers used in the mobile systems are eliminated in favor of fixed pad mounting.

The GBX radar development cost range estimate is based scaling down the new radar design effort needed by leveraging off of the proven heritage radar designs of the AN/TPY-2 phased array and receiver electronics hardware (at a total sunk development cost through FY-09 of $2.3 billion), and an SBX analogous radar turntable. The resulting range estimate of between $0.8 and $1.0 billion is based on the reduced level of system development effort needed for designing GBX system-unique electronics and software to coherently integrate the two arrays, packaging and integrating the two stacked AN/TPY-2 phased arrays onto a turntable, and interfaces for adding an FBX network communications package of already designed electronics and developed software. The estimate also includes producing two system test articles and performing the end-to-end radar testing needed to meet the expected system’s higher power and radar coverage and tracking performance requirements to support MDA’s Integrated Master Test Plan.

The GBX radar procurement cost estimate is based on continuing production using the same AN/TPY-2 radar manufacturing assembly “warm” line currently in place for producing the

Missile Defense Agency's (MDA) funded eleven AN/TPY-2 radar systems needed, and avoiding the non-recurring production costs of re-starting the AN/TPY-2 radar production line and incurring any production start-up tooling, testing and line requalification costs. The average unit cost estimate of MDA's procurement of eleven AN/TPY-2 radars is $181 million with the eleventh unit at $175 million. This build up of the unit recurring cost is based on first extending the AN/TPY-2 production line and applying the same realized manufacturing assembly labor learning cost improvement curve efficiencies for assembling an additional ten dismounted antenna units, cooling equipment units, diesel generator power units, and five modified electronic equipment units, including material cost unit price discounts in buying the quantity of T/R modules and other common parts from the same vendors at the higher total production lot quantities needed. The GBX radar average unit cost for a quantity of five systems is estimated to be $320 million—approximately $139 million higher than the average unit cost estimate of MDA's procurement of eleven AN/TPY-2 radars. The GBX unit costs provide:

- Two antenna units without trailers, two cooling equipment units and two prime power supply units;
- One electronics equipment unit modified to integrate the beam forming and receiving functions of the two antenna units;
- The turntable, its control and associated mounted interface hardware;
- An FBX network communication package; and
- Relatively more complex, additional system integration and end-to-end checkout cost over the AN/TPY-2.

The GBX-specific military construction (MILCON) costs needed before deploying and operating the five new GBX radars was estimated by scaling down the previous costs incurred for constructing the infrastructure facility for the forward-based AN/TPY-2 radar operating in Israel based on assuming each GBX radar will be able to use existing co-located ground radar facilities at the current UEWR (BMEWS) sites noted above.

Finally, the GBX annual operations and support (O&S) estimates were based on adjusting the expenditures MDA provided to the committee for sustaining AN/TPY-2 radars in Israel to reflect use of the operating sites' consolidation of government base security and early warning radar operations and support personnel as well as available standby power from the local electrical grid system already in place at the government sites.

SBX Radar System

Relevant System Investment Costs

The SBX radar as a midcourse defense sensor is capable of providing weapons task plans, in-flight target updates, TOMs and kill assessments. The MDA investment in development of the SBX radar began in FY 2002 with an X-band radar technology development effort focused on providing high-resolution tracking and discrimination data to significantly enhance the GMD fire control and, subsequently, the EKV. The RDT&E funds also covered the development of software algorithms to enhance target discrimination, along with material component enhancements to improve output power and sensitivity. Concurrent with this radar development effort, the SBX program was also initiated, with long-lead parts procurement beginning in FY 2002; procurement of the sea-based platform, main radar structure, radar electronic components, and support equipment and construction of support structures and facilities began the following year. The plan was for delivery of one SBX radar test article for FY 2005. The RDT&E budget also included funds for an IFICS data terminal. The sea-based platform where the SBX was mounted was envisioned to be a modified seagoing, semisubmersible platform similar to the operational oil drilling platforms in use.

Table E-45 summarizes the total investment in the SBX system acquisition costs of $1.7 billion from FY 2002 through FY 2009.

TABLE E-45 SBX Radar System Investment Costs Through FY 2009 (FY 2010 dollars)

	Program Time Frame	Total Investment (billions)	Average Annual Investment (millions)
Sea-based X-band (SBX) radar development[a]	2002-2005	0.4	100
SBX radar system procurement[b]	2002-2005	1.0	245
SBX radar enhancements[b]	2006-2009	0.3	75
Total investment		1.7	

[a]Over a 4-yr period from FY 2002 through FY 2005, $1.4 billion of the $1.7 billion was associated with the SBX-specific X-band advanced technology development effort and concurrent procurement of the SBX radar system test article, modified the sea-based vessel platform, and IDT estimated at system unit cost $980.5 million. (As noted, the annual development funds identified for the X-band advanced technology effort explicitly earmarked for the SBX radar program were allocated as part of the BMD Midcourse Defense Segment program budget from FY 2002 through FY 2005. To the extent possible, the committee's total development cost estimates generated from the MDA RDT&E budget from FY 2002 through FY 2009 were relatively consistent with the total sunk and with FYDP development cost estimates provided by MDA. SOURCE: MDA. 2010. "SBX Joint Cost Estimates Supporting MDA Cost Presentations to NAS," February 28.

[b]The development cost estimated during this 4-yr period is based on funds explicitly identified for the sea-based X-band radar development portion of the BMD Midcourse Defense Segment program's annual MDA RDT&E budgets from FY 2007 through FY 2008 budgets and the FY 2009 sea-based X-band radar program. The SBX radar enhancement from FY 2006 through FY 2009 focused on the following: (1) developing algorithms for discrimination of more complex threat sets and targets; (2) designing material and electronic component enhancements to improve the radar's output power; (3) updating and integrating the SBX software for improving the radar's sensitivity; and (4) performing system integration and ground and flight testing activities.

System O&S Costs

The annual costs for operations and sustainment of the SBX radar and the vessel as an overall system are based on implementing a flexible support strategy with Pearl Harbor, San Diego, and Dutch Harbor as forward-support ports. The sustainment costs include XBR software maintenance, shipyard maintenance and certifications, and sustainment activities for the radar, vessel, and support vessel. The MDA O&S costs provided to the committee do not include the costs of MDA's transition to the Navy planned for FY 2012 and beyond.[61]

MDA provided the committee with an annual O&S cost breakdown from FY 2012 through FY 2017 consisting of overall SBX vessel and radar system estimates for unit personnel, unit operations, maintenance, sustaining support and continuing system improvements.[62] Since

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[61] MDA provided the committee with the SBX program schedule as of February 2010. The schedule identified plans for transition of the Navy as the mission integrator and operator of the offshore SBX support vessel to the Marine Corps as the operator for the SBX vessel. It also identified transferring responsibility from MDA to the Navy as being responsible for funding the X-band radar CLS and system security activities**.**

[62] For its purposes, the committee accounted for MDA's estimates for continuing system improvement of approximately $0.5 million (in then-year dollars) as part of the ongoing development cost estimates for FY 2010 through FY 2015.

these estimates were not transparent with respect to the sustainment costs of the SBX vessel and the offshore support vessel and the SBX radar system itself, the committee provided a summary of the specific annual O&S costs in Table E-46. The FY 2010 and FY 2011 O&S costs listed are based on funds earmarked for these two sustainment activities, as listed in the MDA RDT&E FY-2011 PB and identified in the sea-based X-band radar sustainment program budget justification details.

TABLE E-46 SBX Vessel and Radar System Annual O&S Costs (FY 2010 million dollars)

Fiscal Year	Vessel O&S Costs[a]	SBX Radar System O&S Costs[b]
2010	106	44
2011	107	46
2012[c]	108	47
2013	111	51
2014	109	51
2015	129	63
Average	112	50

[a] The SBX vessel O&S costs include the costs of the SBX and crews for the offshore motor support vessel (the *Dove*), spare parts provisioning, and the lease of the *Dove* for continuing to support ongoing SBX shipboard operations, maintenance, and logistical support activities. These activities include galley and starboard crane upgrades, liquid condition and cooling system modifications, and so on. The activities also include participating in BMDS ground and flight tests. The O&S costs also include activities to support vessel maintenance certifications and the planned procurement of any parts due to the obsolescence of current onboard processors, controls, or displays. In addition, the costs also include onboard system force protection for the SBX and portside security for the SBX and the *Dove*.

[b] The SBX radar O&S costs include costs for sustainment activities for operating and maintaining the X-band radar and associated equipment including the onboard IDT. The O&S costs have included the recent enhancements to the onboard operations control center and installation of the Emergency Radome Pressurization System. The costs include CLS to maintain the onboard primary mission equipment and support to the operation crews.

As part of the estimates for FY 2010 and FY 2011, the committee has included the annual cost of providing sustaining engineering and logistics support (i.e., repairs and spares) for the fielded suite of onboard SBX communications hardware and software for providing 24/7 SATCOM operations.

[c] Since the MDA RDT&E FY 2011 PB did not provide the funding projections for the vessel and SBX radar system for FY 2012 through FY 2015, the committee used the total annual O&S costs provided by MDA for those fiscal years and allocated the costs for each category based on the percentages computed for the FY 2011 funds cited in the budget justification sheets for the SBX sustainment program budgets. (The MDA O&S cost estimates on which the allocations were based were provided in MDA, 2010, "SBX Joint Cost Estimates Supporting MDA Cost Presentations to NAS," February 28. The committee assumed the funds allocated and reported in the budget for FY 2011 closely approximate the projected split of sustainment costs going forward from FY 2012 through FY2015.)

System Life Cycle Costs

From FY 2010 forward, the SBX radar system LCC range estimates for continuing X-band radar development and 20-yr O&S costs of sustaining this ship-based radar system are estimated at between $2.1 billion and $2.9 billion (Table E-47). The total estimate from FY 2010 forward includes the following:

- Requested funding of approximately $1.1 billion for FY-2012 FYDP PB from FY 2010 through FY 2016 for the SBX development and support program, and
- Sustainment funding for operating and maintaining the SBS radar system over a 20-yr service life.

TABLE E-47 SBX Ship-Based Radar System Total LCC Estimate (FY 2010 billion dollars)

	Minimum	Maximum
Development[a]	1.1	1.9
Procurement[b]	Not applicable	Not applicable
Force quantity buy	1	1
MILCON	None required	None required
20-yr O&S[c]	1.0	1.0
Total 20-yr LCC estimate	2.1	2.9

[a] The SBX system development lower bound, or minimum, cost estimate of $1.1 million accounts for the efforts from FY 2010 through FY 2016 for MDA funds focused on (1) developing and providing system engineering and X-band radar advanced discrimination algorithms and software build releases for SBX system integration and testing, and (2) demonstrating this SBX target tracking capability on planned flight interceptor tests by acquiring the targets of opportunity and sending tracking reports to the GMD fire control.

The upper bound, or maximum, development cost estimate of $1.9 billion adds $0.8 billion for continuing this SBX-specific radar development effort based on extending the average annual FY 2012 FYDP budget request of $160 million for at least 5 more years through FY 2020.

[b] Procurement cost is not separately identified from the Development Cost.

[c] The total O&S cost for sustaining the ship-based SBX radar systems over a 20-yr service life is estimated at $1.0 billion based on applying an average sustainment cost estimate of $50 million over the 20-yr service life of this system. The SBX radar O&S estimate includes costs for operating and maintaining the X-band radar and associated equipment for the onboard IDT.

INTERCEPTOR UNIT PRODUCTION COST DETAILS

Aegis SM-2

Even though the first 71 SM-3 Block 1A interceptors were produced using RDT&E funds, the average missile unit costs are based on reported annual procurement budgets and lot quantity buys beginning in FY 2009. By the end of FY 2010, 41 SM-3 Block IAs were expected to be in inventory. The cumulative average unit cost of the last two lots of the SM-3 Block IA missiles is estimated at $9.6 million in FY 2010 dollars.

“SM-3 Block IA provides [greater] capability over [Block I] to engage short- to intermediate-range ballistic missiles. [The design] incorporates rocket motor upgrades and computer program modifications to improve sensor performance, and missile guidance and control. . . .It . . . includes producibility and maintainability features required to qualify the missile as a tactical fleet asset.”[63]

Even though the first 34 SM-3 Block IB interceptors were produced using RDT&E funds, the average missile unit costs are based on reported annual procurement budgets and lot quantity buys beginning in FY 2011 and going forward through FY 2015. The projected cumulative average unit cost for the total quantity buy of 290 missiles over the 5-yr production is estimated at $9.3 million.

SM-3 Block IB incorporates a two-color, all reflective IR seeker, enabling longer range acquisition and increased threat discrimination. The missile is configured with a throttleable DACS (TDACS) to provide a more flexible and lower cost alternative to the solid DACS.

Table E-48, a repeat of E-32, provides the detailed estimates by fiscal year for these two blocks of Aegis missile interceptors.

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[63] See Raytheon news release: “Raytheon Missiles Engage Ballistic Missile and Airborne Targets Over the Pacific Ocean,” April 26, 2007.

TABLE E-48 SM-3 Average Unit Procurement Cost Summary (FY 2010 million $)

	Cumulative Average Unit Cost	Total Quantity	Fiscal Year	Annual Lot Quantities	Average Unit Cost per Lot
SM-3 Block IA	9.6	41	FY 2009	23	9.3
(last two lots)			FY2010	18	10.0
SM-3 Block IB	9.3	290	FY 2011	8	11.6
			FY 2012	66	10.3
			FY 2013	72	9.4
			FY 2014	72	8.8
			FY 2015	72	8.5

Figure E-8 plots cumulative average unit procurement cost as a function of production quantity for the SM-3 Block IA missiles along with the computed best-fit learning, or CIC slope for this missile block build extended forward for a total buy quantity of 134. The CIC slope is computed at 94.5 percent, with a first unit or T_1 cost of $13.7 million in FY 2010 dollars.

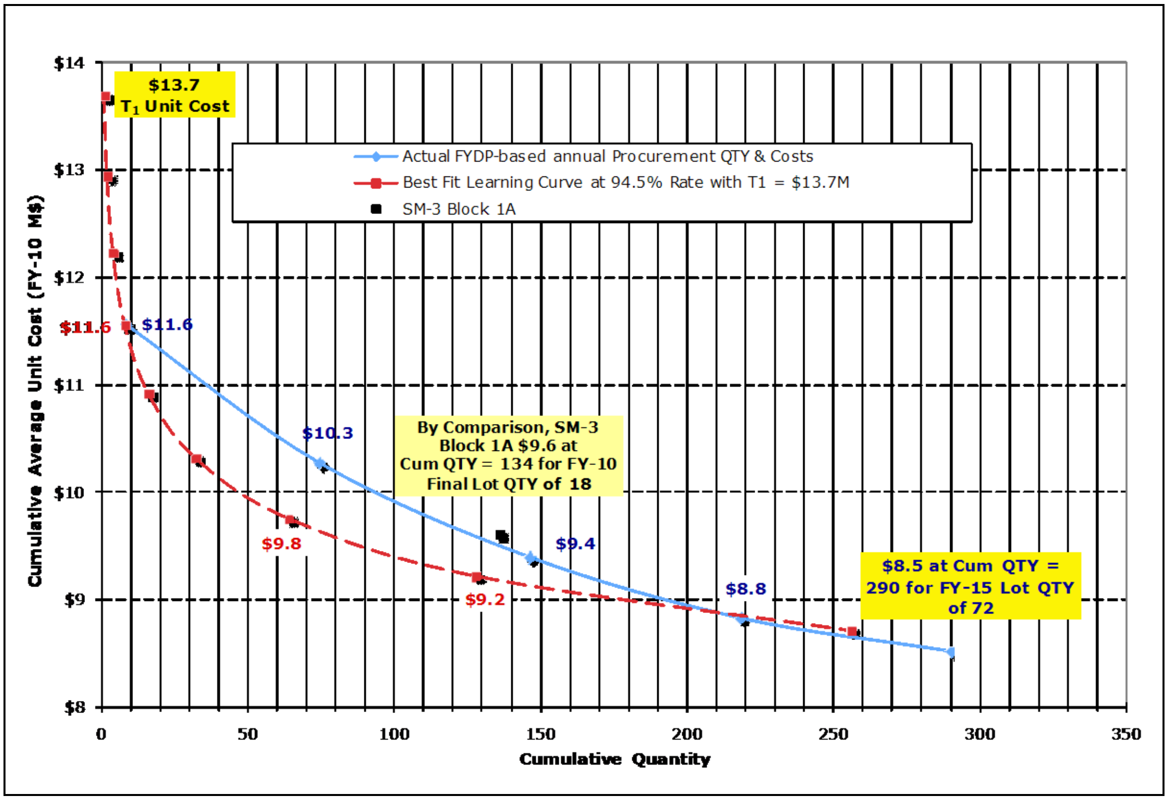

FIGURE E-8 Aegis SM-3 Block IA missile. Cumulative average unit cost learning curve.

Terminal High-Altitude Area Defense

Each THAAD battery consists of a basic load of 48 interceptors, 6 launchers, TFCC housed in 2 TSGs, and peculiar and common support equipment.

Even though the first 50 THAAD interceptors were produced using RDT&E funds, the average missile unit costs are based on reported annual procurement budgets and lot quantity buys beginning in FY 2010 and continuing at the rate of 72 per year from FY 2013 through FY

2015. The FY 2011 budget plans were based on having 26 THAAD (operational) interceptors in inventory by the end of FY 2010.

Table E-49 below provides the detailed estimates by fiscal year the THAAD missile interceptors.

TABLE E-49 THAAD Missile Average Unit Procurement Cost Summary (FY 2010 million dollars)

	Cumulative Average Unit Cost	Total Quantity	Fiscal Year	Annual Lot Quantities	Average Unit Cost per Lot
THAAD interceptor	9.2	161	FY2010	26	10.5
			FY2011	63	9.3
			FY2012	72	8.6

Figure E-9 plots cumulative average unit procurement cost as a function of production quantity for the THAAD missile, along with the best-fit” CIC slope for the missiles block build extended forward for a total buy quantity of 134. The CIC slope is computed at 94.5 percent with a first unit, or T_1, cost of $13.7 million in FY 2010 dollars.

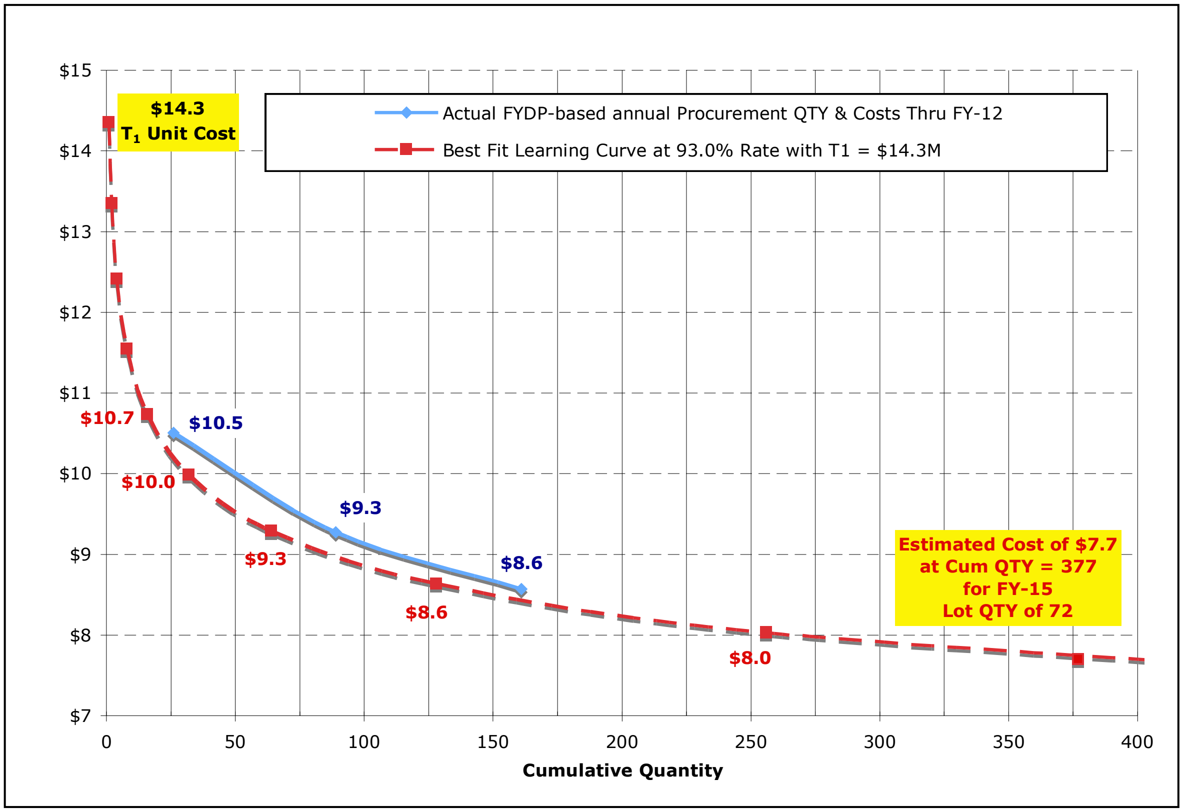

FIGURE E-9 THAAD missile. Cumulative average unit cost learning curve.