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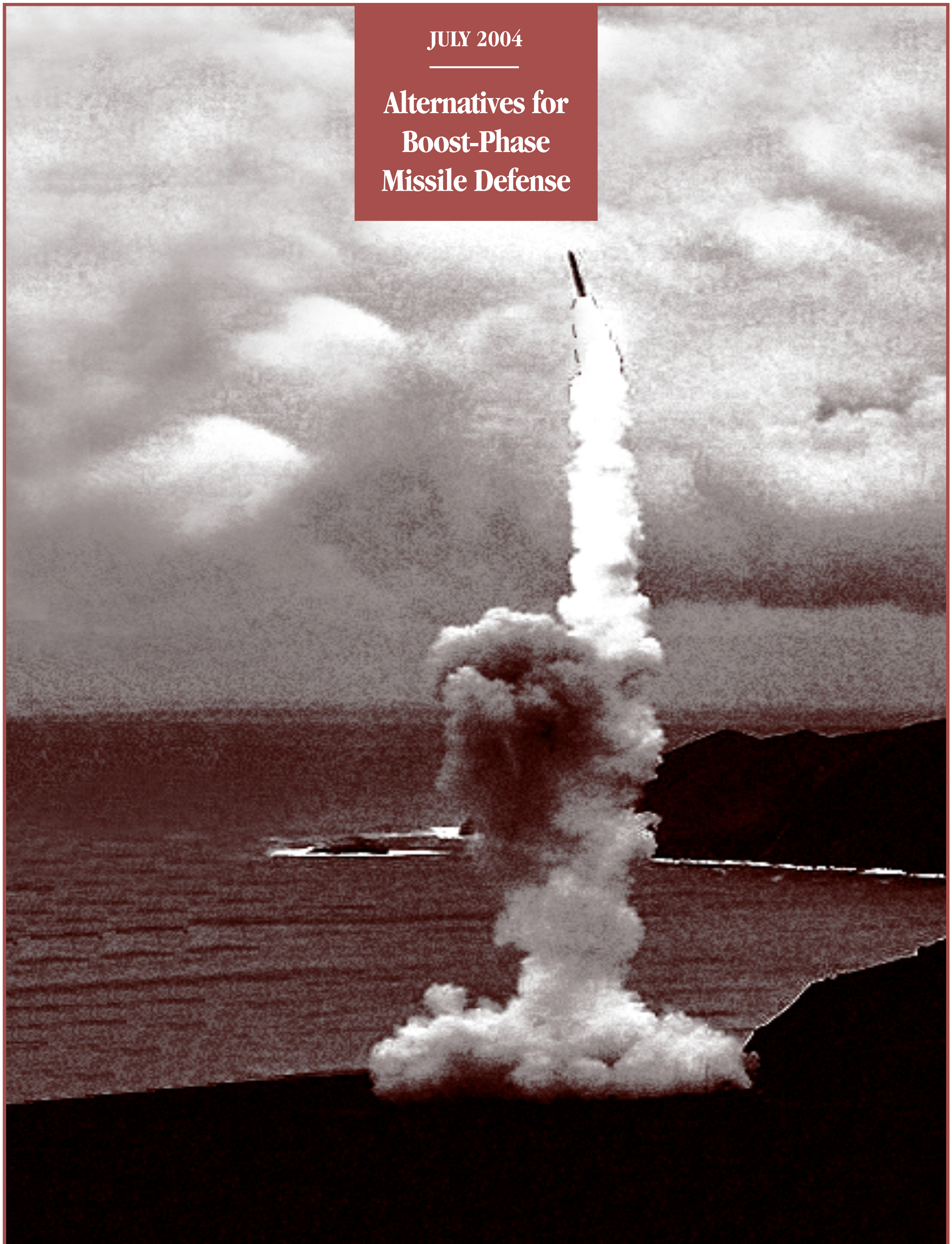

JULY 2004

Alternatives for Boost-Phase Missile Defense

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The Congress of the United States ■ Congressional Budget Office

Notes

Numbers in the text and tables of this report may not add up to totals because of rounding.

Unless otherwise indicated, all dollar figures are in 2004 dollars.

The cover shows an intercontinental ballistic missile (a U.S. Minuteman III being test launched from Vandenberg Air Force Base in California) in the first seconds of the boost phase of its flight. (Photo by the U.S. Air Force)

Preface

A prominent part of the Bush Administration's strategy for national defense is developing and fielding defenses against ballistic missiles. To that end, the Department of Defense's Missile Defense Agency (MDA) is pursuing a layered defense composed of various systems capable of intercepting ballistic missiles at different points in their flight. For the past several years, work has primarily focused on intercepting long-range missiles during their midcourse phase (after their booster rockets have burned out but before their warheads have reentered the atmosphere). MDA plans to field initial elements of a midcourse system this year. Recently, the agency also began an effort to develop interceptors capable of hitting intercontinental ballistic missiles during their boost phase (the first few minutes after launch, before their booster rockets burn out).

This Congressional Budget Office (CBO) study—prepared at the request of the Subcommittee on Emerging Threats and Capabilities of the Senate Armed Services Committee—looks at technical, operational, and cost issues related to using a boost-phase intercept (BPI) system to defend the United States against intercontinental ballistic missiles. The study compares the strengths, weaknesses, and costs of five alternative designs for a BPI system—three surface-based and two space-based—that span a range of performance characteristics. In keeping with CBO's mandate to provide objective, impartial analysis, this study makes no recommendations.

David Arthur and Robie Samanta Roy of CBO's National Security Division wrote the study under the general supervision of J. Michael Gilmore. Raymond Hall of CBO's Budget Analysis Division prepared the cost estimates and wrote Appendix A under the general supervision of Jo Ann Vines. Adrienne Ramsay and Robert Schingler helped review the manuscript for factual accuracy. Eric Wang, Barbara Edwards, David Moore, Elizabeth Robinson, and Christopher Williams provided thoughtful comments on early drafts of the study, as did Maile Smith of the Institute for Defense Analyses and Professor Daniel Hastings of the Massachusetts Institute of Technology. (The assistance of external participants implies no responsibility for the final product, which rests solely with CBO.)

Christian Spoor and Leah Mazade edited the study, and Christine Bogusz proofread it. Maureen Costantino produced the cover and graphics and prepared the study for publication. Lenny Skutnik printed the initial copies, and Annette Kalicki prepared the electronic versions for CBO's Web site (www.cbo.gov).

Douglas Holtz-Eakin
Director

July 2004

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Developing and fielding defenses against ballistic missiles are significant priorities of the Department of Defense (DoD) under the current Administration. Missile defenses are considered important protection against a growing threat that rogue nations might obtain weapons of mass destruction and use ballistic missiles to fire them at U.S. forces abroad, U.S. allies, or the United States itself. DoD's Missile Defense Agency (MDA) is pursuing a layered strategy for ballistic missile defense, in which different defensive systems would target threat missiles at different phases in their flight. The premise is that even if technological limitations prevented any single layer from offering the desired level of protection, multiple layers could together provide an effective defense.

In the case of intercontinental ballistic missiles (ICBMs) that might be launched at the United States, MDA has focused on developing a system to intercept ICBM warheads in the midcourse phase of their flight. It plans to field such a system in late 2004. Last year, MDA also began an effort to develop defenses that would intercept ICBMs during their boost phase—the first few minutes of flight. The agency's current plans for such a boost-phase intercept (BPI) system focus on building mobile, surface-based defenses that would operate from sites on land or on ships, but it also plans to investigate space-based systems.[1]

The Congressional Budget Office (CBO) estimates that a BPI system that could counter liquid-fuel ICBMs launched from anywhere in both North Korea and Iran —the representative threats used in this analysis—would cost between $16 billion and $37 billion (in 2004 dollars) to develop, produce, and operate for 20 years if the system used surface-based interceptors. If the interceptors were based on orbiting satellites, those costs would range from $27 billion to $78 billion, CBO estimates. If the system was scaled back to defend against missiles from only one of those countries, costs would be lower. Conversely, if the system needed to counter solid-fuel missiles—which have a shorter boost phase than liquid-fuel missiles do—costs could rise.

DoD has not articulated the specific capabilities required for a BPI system. This analysis looks at how various levels of system performance translate into different levels of operational effectiveness. On the basis of those relationships, this study defines five alternative BPI systems—three surface-based and two space-based—that might be fielded to defend the United States against attack by ICBMs and compares their operational strengths and weaknesses as well as their costs.

The alternative systems span a range of capability, from the current state-of-the-art performance to more-advanced performance characteristics that have been proposed but not yet developed. Comparing the potential effectiveness of each option illustrates the operational benefits that might be realized by assuming greater technical risk in pursuit of higher system performance. Of course, the value of better performance depends on the kinds of threats to be countered. This analysis is not based on a specific prediction about future threats. Rather, it assesses operational effectiveness against a range of potential threats that reflects the uncertainty in how hostile countries' ballistic missile capabilities might evolve in coming years.

Ballistic Missiles and Boost-Phase Intercept

Ballistic missiles consist of a warhead and a guidance system mounted on a rocket motor, or booster. When an ICBM is launched, the rocket propels it up and out of the atmosphere at a high speed (typically 6 to 7 kilometers per second). Once the missile is out of the atmosphere

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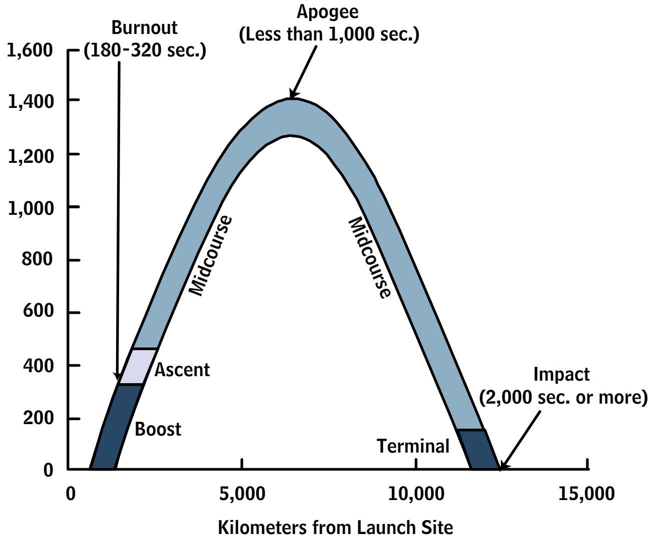
1. MDA is also developing another BPI system, called the Airborne Laser. Although that system may have some capability against ICBMs, it is primarily intended to counter shorter-range ballistic missiles, which are not the focus of this study.

Summary Figure 1.

Trajectory of a Notional ICBM

(Altitude in kilometers)



Source: Congressional Budget Office.

Note: ICBM = intercontinental ballistic missile.

and its rocket motor has shut down, the booster is jettisoned. The warhead then travels an unpowered, ballistic trajectory to its target (much like a basketball's trajectory to the hoop after it leaves a player's fingertips).

Ballistic missile trajectories are typically divided into three phases. The first is the boost phase, which lasts from the missile's launch until the rocket booster shuts down, or "burns out" (see Summary Figure 1). For ICBMs, which typically have two- or three-stage boosters, the boost phase lasts until the final stage burns out. The second, or midcourse, phase lasts from the end of boost until the warhead reenters the atmosphere. (The early portion of the midcourse phase, after the booster burns out but before the warhead is deployed, is sometimes called the ascent or early-ascent phase.) The final, or terminal, phase lasts from reentry until the warhead reaches its target.

The objective of midcourse and terminal defenses is to hit and destroy the warhead. In the case of boost-phase defenses, however, destroying or damaging the booster alone may prevent the warhead from achieving enough velocity to reach its target. Of course, destroying the warhead is preferable because a warhead that falls short of its intended target may still cause serious damage elsewhere.[2] An intercept occurring in the ascent phase will need to destroy the warhead or prevent the warhead from separating from the booster.

Boost-phase intercept is an attractive missile defense alternative because, during boost, a ballistic missile is comparatively easy to detect and track. The hot plume put out by the booster rocket presents a large target for infrared sensors, and the rocket body itself is larger and more visible to infrared sensors and radar than is the much smaller warhead that remains once the booster is jettisoned. In addition, countermeasures on a missile, such as decoys designed to distract defensive systems, are more difficult to deploy before the booster burns out.

This year, the Missile Defense Agency is spending $118 million, or 1.5 percent of its budget, on developing kinetic-energy boost-phase interceptors to counter ballistic missiles, including ICBMs. Those interceptors would employ the "hit to kill" concept, using precise homing to fly a "kill vehicle" into a target (akin to a bullet hitting a bullet). Because of the velocities involved, such collisions can release far more kinetic energy than the chemical energy of a similarly sized explosive warhead. Under MDA's five-year budget plan, annual funding for that effort would grow to $2.2 billion by 2009 (in 2004 dollars), or 28 percent of the agency's projected budget in that year (see Summary Table 1). Most of that money would go toward building mobile, surface-based systems, but a total of about $700 million over the next five years would be devoted to investigating the feasibility of a space-based BPI system.

The challenge of boost-phase intercept is the very short time available for the engagement: typically four to five minutes in the case of liquid-fuel ICBMs and three minutes or less in the case of solid-fuel ICBMs, which accel-

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[2] Contrary to popular impression, a ballistic missile intercepted in its boost phase usually will not fall on the country that launched it. However, if the boost-phase interceptor cannot reliably destroy the warhead, uncertainty about how long the booster is supposed to burn and when the warhead is supposed to separate from the booster can make it difficult to ensure that the warhead does not fall on a location short of its target but still within the United States or another friendly country.

Summary Table 1.

Funding for the Missile Defense Agency's Ballistic Missile Defense System Interceptors Program, 2004 to 2009

(Billions of 2004 dollars)

	2004	2005	2006	2007	2008	2009	Total, 2004-2009
Budget for BMDS Interceptors Program	0.1	0.5	1.1	1.6	2.0	2.2	7.6
Total MDA Budget	7.6	9.0	8.3	9.6	7.9	7.9	50.3
Memorandum:							
BMDS Interceptors as a Percentage of MDA's Budget	1.5	5.6	12.9	16.8	25.5	27.8	15.2

Source: Congressional Budget Office based on a briefing by staff of the Missile Defense Agency, March 4, 2004.

erate faster.[3] The time available for intercept—coupled with the distance that an interceptor must travel to reach its target, which results from the geography of a particular scenario—determines the response time and interceptor speed needed for a BPI system.

In general, more-technologically advanced ICBMs and larger threat countries require higher-performance surface-based BPI systems. More-advanced ICBMs usually have shorter burn times (that is, boost phases). And against a larger country, interceptors will have to fly farther to reach ICBMs launched from deep inside the country's borders. The performance requirements of a system can be eased by locating BPI sites in the general path that a threat ICBM would fly to reach the United States, because such locations would improve the geometry of the engagement.

The feasibility of boost-phase intercept is a subject of wide disagreement. That disagreement stems in part from differing views of what would constitute an operationally useful system. Some people argue that the potential proliferation of more-challenging targets, such as solid-fuel ICBMs with short burn times, necessitates a very capable—and thus technically challenging and expensive—BPI system. In their view, a less-capable BPI system that could not counter such threats might be obsolete before it was fielded. That position was emphasized in a 2003 report by the American Physical Society (APS).[4] Others argue that solid-fuel ICBMs are far in the future for any country other than a highly developed one. In that view, less-capable BPI systems would be useful to counter longer-burning liquid-fuel ICBMs, which might proliferate in the meantime.

This study does not make assumptions about a specific future threat or about how an adversary might react to U.S. deployment of boost-phase missile defenses. Instead, it considers what capability would be provided—and at what cost—by several alternative BPI systems against both liquid- and solid-fuel ICBMs under a variety of engagement conditions.

Operational Effectiveness of BPI Systems

A BPI engagement can be conceptually divided into two stages. The first is the commit stage, which lasts from when the threat missile is launched until a boost-phase interceptor is fired. During the commit stage, the system must detect its target, track it, and decide to commit an

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[3] Those times are typical ones available for intercept. Actual boost times will vary depending on the characteristics of a particular ICBM. More time may be available if the BPI system can engage the ICBM in its early-ascent phase. Conversely, less time may be available if the system has to hit the booster before the ICBM has reached top speed. Recognizing those considerations, this report for simplicity refers to intercepts as occurring "at booster burnout."

[4] *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues* (Washington, D.C.: American Physical Society, July 2003), available at www.aps.org/public_affairs/popa/reports/nmd03.cfm.

interceptor to an engagement. The second stage is the flyout stage, which lasts from when the interceptor is launched until it reaches (and, if all goes well, destroys) its target.

Dividing the overall engagement time differently between the commit and flyout stages could yield different BPI systems with similar overall effectiveness. For example, designers could compensate for a system that took longer to commit by producing faster interceptors, or they could make up for slower interceptors by speeding up a system's commit time. Alternatively, the total time available for an intercept might be extended by incorporating the capability to hit a missile in its early-ascent phase.

CBO evaluated those trade-offs in performance by comparing the number of BPI launch locations that would be needed to provide a complete defensive layer (full coverage) against a threat country under different combinations of commit times and interceptor speeds. A BPI system that provided full coverage of a threat country would be able to engage an ICBM launched at any target in the United States from anywhere inside that country. Full coverage would also mean that a BPI system could not be easily circumvented by mobile ICBM launchers. The number of launch locations needed for such a system can be used to compare the cost and operational complexity of particular BPI designs.

In its analysis, CBO assessed the capability of potential BPI systems against both liquid- and solid-fuel ICBMs. The representative liquid-fuel ICBM used in this analysis has a similar performance—about a five-minute burn time—to that of the 1960s-era U.S. Titan II or Russian SS-12 missile. The representative solid-fuel ICBM—with about a three-minute burn time—is comparable to the current U.S. Minuteman III or Russian SS-25 missile. Those representative times are slightly longer than the ones assumed in much of the 2003 APS report (about four minutes for liquid-fuel ICBMs and 2.8 minutes for solid-fuel ICBMs). Although those five-minute and three-minute values are booster burn times, there is uncertainty about whether an intercept would always occur when a booster was burning, and CBO's analysis implicitly incorporates that uncertainty. For example, the results for engaging a missile within a five-minute burn time would be similar (to a reasonable approximation) to the results for engaging a missile within a four-minute burn time plus a one-minute early-ascent phase.[5]

The size and location of potential threat countries play a role in determining the effectiveness of a BPI system by determining the distance that an interceptor must fly to reach its target. Thus, comparisons of alternative systems must be made in the context of specific potential threats. This study evaluates the effectiveness of different BPI systems against a representative threat: ICBMs fired at the United States from Iran and North Korea. Those countries were chosen because their geographic characteristics pose challenges to different kinds of BPI systems and because they are known to be pursuing long-range-missile capability.

Surface-Based BPI Systems

Depending on their commit time and interceptor speed, the range of surface-based BPI systems that CBO analyzed would need two to four launch sites to provide full coverage against a liquid-fuel ICBM fired from Iran (see Summary Figure 2).[6] If two launch sites were needed, they could be located in Iraq to the east and Afghanistan to the west. If additional sites were necessary, they might be located in Turkmenistan to the north and on a ship in the Persian Gulf or the Gulf of Oman to the south.

CBO evaluated a range of commit times from zero to 90 seconds. A zero commit time—which means that an interceptor takes off at precisely the same moment as the ICBM it is targeting—is an ideal case that could not be achieved in practice. CBO included it to provide a lower limit. The upper end of the range, 90 seconds, represents a long delay in committing, which places stringent demands on the interceptor portion of a BPI system.

In addition, CBO looked at interceptor speeds ranging from 6 kilometers per second to 10 km/sec (under the assumption that interceptors would accelerate to those top speeds in 60 seconds). The defensive coverage provided by a BPI interceptor decreases dramatically below the low-end speed of 6 km/sec. The main reason is that

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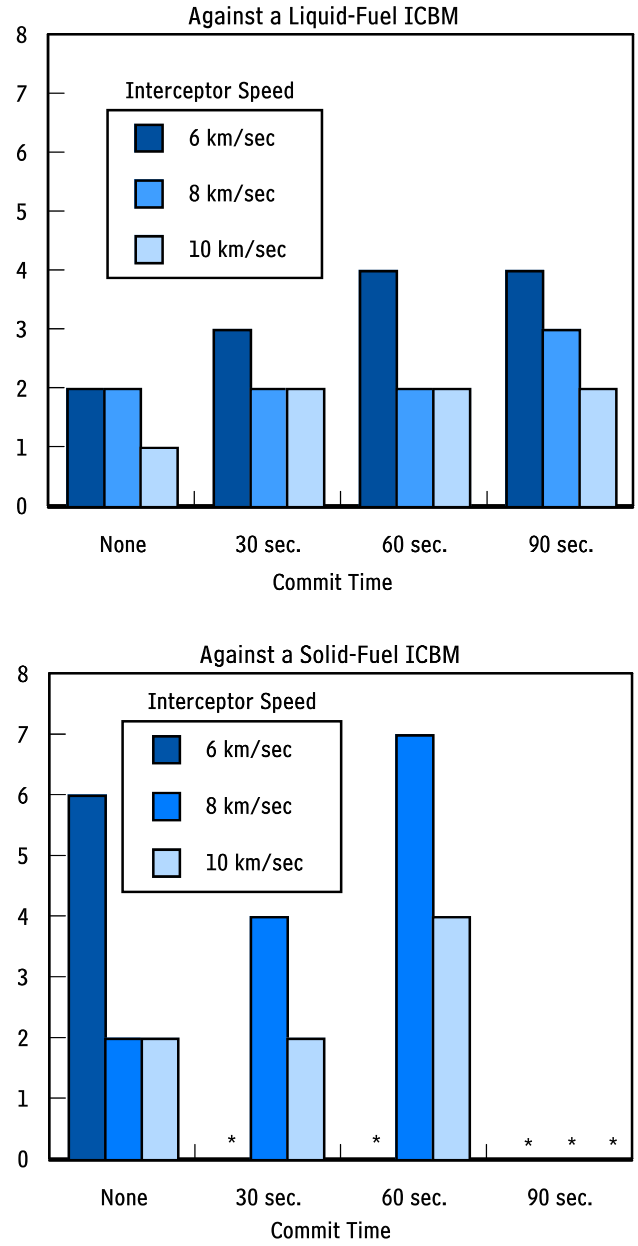
[5] Although similar, the results would differ because an ICBM with a four-minute burn time would have a different acceleration profile than that of an ICBM with a five-minute burn time. However, that difference is smaller than the uncertainty about what the burn time of future threat ICBMs might be.

[6] At a minimum, a surface BPI site would consist of some number of interceptors and their launchers plus communications equipment for linking the site to sensor information from other parts of the missile defense system and for communicating guidance information to the interceptor while it was in flight.

Summary Figure 2.

Number of Surface-Based BPI Sites Needed for Full Coverage of Iran, by Commit Time and Interceptor Speed



Source: Congressional Budget Office.

Notes: The figures assume that interceptors have a burn time of 60 seconds.

* = full coverage not possible; BPI = boost-phase intercept; ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

ICBMs reach speeds of 6 to 7 km/sec as they near burnout, and an interceptor moving significantly slower than its target can hit that target only under a narrow set of engagement conditions. Interceptors faster than the high-end speed of 10 km/sec are too large to make their deployment to a theater practical.

In the case of CBO's representative solid-fuel ICBM, with its shorter burn time, the trade-offs inherent in designing an effective BPI system are more constrained. In general, because less time is available to reach the target, more BPI sites are needed so interceptors can have a shorter flyout distance. However, under several of the combinations of system characteristics that CBO examined, full coverage would not be possible against a solid-fuel ICBM launched from Iran. For example, at no speed between 6 and 10 km/sec could interceptors engage such an ICBM if the system's commit time was 90 seconds (see Summary Figure 2). Even with a 60-second commit time, a system with 10-km/sec interceptors would require four sites to fully cover Iran, and one with 8-km/sec interceptors would need seven sites.[7] A system with 6-km/sec interceptors would require a commit time of less than 30 seconds as well as a large number of sites to cover Iran.

North Korea is much smaller than Iran, so it would pose fewer difficulties for a surface-based BPI system. CBO's analysis indicates that a single site with 6-km/sec interceptors located on a ship in the Sea of Japan could defend against a liquid-fuel ICBM launched from anywhere in North Korea, even with commit times as long as 90 seconds. Against a solid-fuel ICBM, the commit time would need to be 30 seconds (in the case of 6-km/sec interceptors) or 60 seconds (in the case of 8-km/sec interceptors) for that site to provide full coverage.

Space-Based BPI Systems

The factors that determine coverage for a space-based BPI system are different, although commit time and interceptor speed still play a role. A space-based system would most likely be a constellation of interceptor satellites located in low-Earth orbit at an altitude of about 250 km to 300 km. Higher orbits would require greater launch costs and be farther from the intended targets. At lower orbits, satellites would have shorter life spans because of

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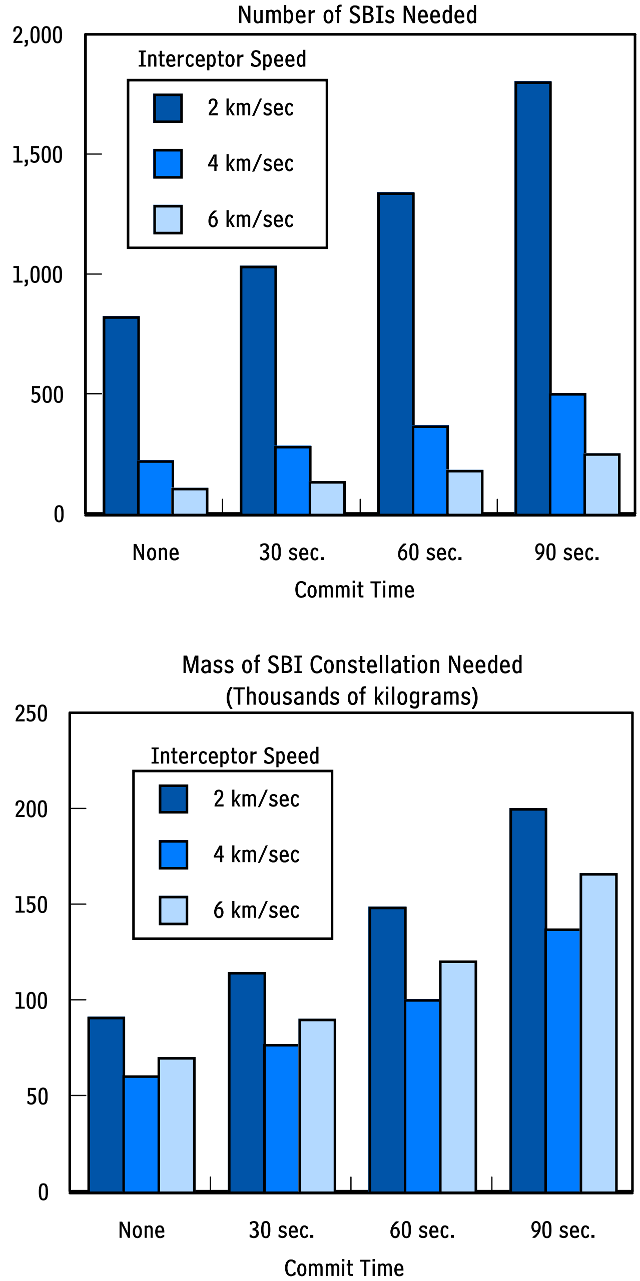
[7] Although it used slightly different assumptions, the APS study also concluded that interceptors with velocities of around 10 km/sec might be able to counter Iranian solid-fuel ICBMs.

Summary Figure 3.

Characteristics of SBI System Needed for Full Coverage of North Korea and Iran Against a Single Liquid-Fuel ICBM



Source: Congressional Budget Office.

Notes: The figures are based on using a two-shot salvo against a single liquid-fuel ICBM. They assume that interceptors have an acceleration of 10g and that kill vehicles have a mass of 30 kilograms.

SBI = space-based interceptor; ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

atmospheric drag. Satellites in inclined low-Earth orbits are not fixed over one spot but instead follow a sinusoidal ground track as they move over the Earth. Thus, providing full coverage of a specific threat country requires having a constellation of space-based interceptors (SBIs) with their orbits positioned such that at least one SBI is capable of reaching the threat at any given time.

That orbital reality is at the root of both the main advantage and disadvantage of space basing for boost-phase intercept. On the positive side, space basing can provide BPI access to any point on Earth, including the interiors of very large countries that could never be reached with a surface-based interceptor launched from an adjacent country. On the negative side, although SBI constellations can be tailored to focus on specific latitude bands, they cannot be concentrated against individual countries.

The number of space-based interceptors needed to cover a threat country depends on the performance of the system (which determines the coverage area, or footprint, of each satellite) and the latitude of the country. Covering higher latitudes generally requires more satellites because their orbits must traverse more of the Earth's surface, forcing the satellites to spend more time over locations other than the threat country.

Depending on commit time and interceptor speed, a constellation capable of providing full coverage against both North Korean and Iranian liquid-fuel ICBMs would require anywhere from about 130 to 1,800 interceptors (see Summary Figure 3). Those results assume that two interceptors would be available to be fired at each ICBM to increase the probability of intercept—a tactic consistent with MDA's plans for its BPI system.[8] (The analysis of surface-based systems above did not specify two-shot salvo tactics because the results of that analysis were presented in terms of number of launch locations, each of which could have one or more interceptors available.) Additional SBIs would be needed if the threat country launched more than one ICBM almost simultaneously.

CBO examined the same range of commit times for a space-based system as it did for a surface-based system because both types of systems would probably rely on a similar infrastructure of missile defense sensors. However, CBO used a lower range of interceptor speeds in the SBI

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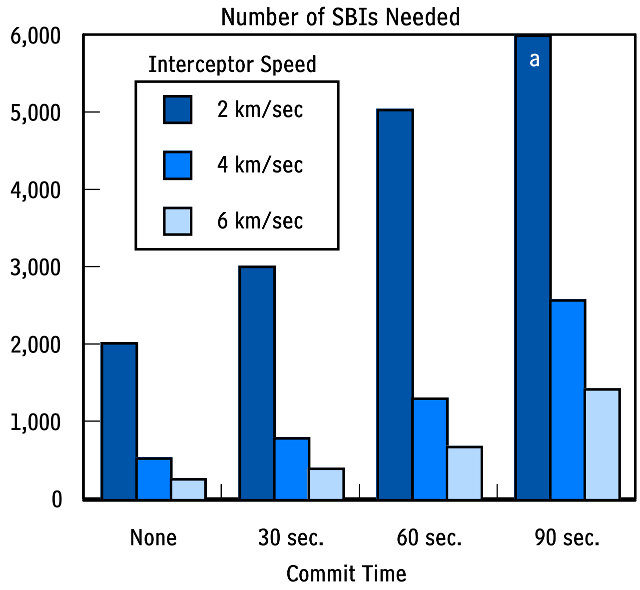
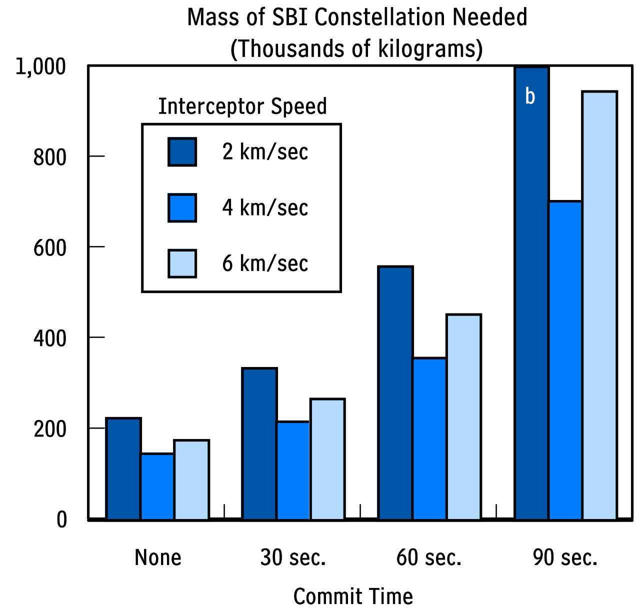
[8] "KEI Contractors Borrow from Other MDA Programs to Meet Schedule," *Inside the Pentagon*, April 15, 2004, p. 1.

Summary Figure 4.

Characteristics of SBI System Needed for Full Coverage of North Korea and Iran Against a Single Solid-Fuel ICBM





Source: Congressional Budget Office.

Notes: The figures are based on using a two-shot salvo against a single solid-fuel ICBM. They assume that interceptors have an acceleration of 10g and that kill vehicles have a mass of 30 kilograms.

SBI = space-based interceptor; ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

a. Actual number of SBIs is 10,909.

b. Actual mass is 1,208,000 kilograms.

analysis—2 km/sec to 6 km/sec—to minimize the total mass of the hardware that would have to be launched into orbit, an important consideration because of launch costs. A smaller number of faster SBIs does not necessarily result in a lower total mass than a larger number of slower SBIs. Whether it would be more cost-effective to deploy a lighter constellation with many moderate-performance SBIs or a heavier constellation with fewer higher-performance SBIs would depend on the relative production and launch costs.

Providing full coverage against solid-fuel ICBMs requires a larger number of SBIs than is the case against liquid-fuel ICBMs. The shorter burn time of solid-fuel ICBMs results in a smaller effective footprint for each SBI. To maintain coverage, the separation between interceptors must shrink, which means that the size of the constellation must increase. Constellations as large as 5,000 SBIs (with a 60-second commit time and 2-km/sec interceptors) or as heavy as about 1,000 metric tons (with a 90-second commit time and 6-km/sec interceptors) might be necessary (see Summary Figure 4). On the basis of mass alone, a constellation of 1,000 metric tons would require more than 40 launches on Delta-IV (Heavy) or Atlas-V (Heavy) rockets, the largest expendable launch vehicles being planned.

The BPI Options Examined in This Analysis

For this study, CBO developed five alternative systems—three surface-based and two space-based—to compare the potential effectiveness and cost of different approaches to boost-phase intercept by kinetic-energy interceptors. Each system has the following capabilities:

- *The ability to counter a representative liquid-fuel ICBM from North Korea or Iran.* Although neither country is known to possess ICBM-class ballistic missiles today, both are developing long-range missiles based on liquid-fuel technology. North Korea has tested (with only partial success) the Taep'o-dong 1, a missile thought to have a range of 5,000 km. Iran is believed to be working on extended-range versions of its Shahab-series ballistic missiles (although they appear to remain short of intercontinental range). In addition, both North Korea and Iran have expressed their intention to develop space-launch systems. Such systems would be suitable for use as ICBMs.

- *Coverage of all possible ICBM launch locations in North Korea and Iran.* The ability to cover all locations in a country means that a BPI system could not be easily circumvented by mobile ICBM launchers. A system able to fully cover Iran and North Korea would be highly capable against most other potential threat countries employing similar ICBM technology. Iran poses a particular challenge for a surface-based BPI system because it is the 16th largest country by area. (Many of the larger countries are considered unlikely to prove a threat to the United States.) North Korea poses a particular challenge for a space-based system because its high latitude necessitates a large constellation of interceptors. A space-based system with orbits capable of covering North Korea could cover about 75 percent of the world's countries and about 90 percent of those that might now be considered potential threats.

The first step in boost-phase intercept is detecting the launch of a threat missile. CBO's alternative systems are assumed to all use the same set of sensors to detect launches—a sensor architecture based on the one that DoD is planning to deploy to support missile defense and other requirements. For BPI, the important sensors are the system of space-based infrared satellites (called SBIRS-High) now being developed. CBO assumed that such space-based sensors could allow for BPI commit times on the order of 60 seconds (on the basis of the APS study's assessment of the potential performance of notional satellite sensors employing current technology).[9] Sensors such as surface or airborne radar could be effective against small countries like North Korea. However, because of horizon limitations, an ICBM launched from the interior of a large country such as Iran might not be visible to surface or airborne sensors for more than two minutes—resulting in too long a commit time for BPI.

Because the sensor architecture is common to all of the alternatives, it is not explicitly included in the comparison below. Nonetheless, the analysis assumes that SBIRS-High or a system with similar capability would be fielded in time to support these illustrative BPI systems.

Option 1: 6-km/sec Surface-Based Interceptors

Option 1 is representative of a system that might be developed if getting defenses into the field as soon as possible was a critical consideration. This system is similar in booster performance to the one MDA is developing.[10]

Like the other alternatives, Option 1 provides the capability to handle liquid-fuel ICBMs fired from a large fraction of potential threat countries (see Summary Table 2). Although its interceptors have high performance—a speed of 6 km/sec and peak acceleration of around 22g (22 times the Earth's gravitational pull)—they should not require great advances in booster technology. Likewise, the 140-kilogram (kg) kill vehicle should not require technically challenging miniaturization. Moreover, the interceptors, which weigh just over 3,000 kg each, can be transported by air.

Option 2: 8-km/sec Surface-Based Interceptors

Option 2 fields faster interceptors than Option 1. A lighter kill vehicle enables the interceptors to fly faster without a dramatic increase in booster size. Option 2 assumes that additional research and development will take place to produce a significantly lighter kill vehicle. Because of that additional research, Option 2's BPI system might take longer to develop and field than Option 1's, for a given rate of investment spending.

Option 2 is representative of a system that might be developed if solid-fuel ICBMs were considered a likely threat or if reducing the number of sites needed to cover large threat countries was an important consideration. Additionally, with their higher speed, Option 2's interceptors might be suitable for use in midcourse defenses.

Option 3: 10-km/sec Surface-Based Interceptors

Option 3 represents a system designed primarily to counter solid-fuel ICBMs. It fields the fastest interceptors of any of the surface-based systems considered—10 km/sec—because of the short engagement times available against solid-fuel ICBMs. These interceptors use the same lightweight kill vehicle as in Option 2, but they require a significantly larger and higher-performance booster to achieve their higher speed. As a result, they have nearly five times the mass of the interceptors in Option 2: over 17,000 kg each. The technical challenges

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[9] That study estimated that current space-based missile warning sensors (the Defense Support Program satellites) could also support BPI detection but with longer commit times.

[10] Terry Little, "Kinetic Energy Interceptors Overview" (unclassified briefing by the Missile Defense Agency to Congressional Budget Office staff, November 13, 2003).

Summary Table 2.

Characteristics, Cost, and Effectiveness of Alternative Systems for Boost-Phase Intercept

	Surface-Based Systems			Space-Based Systems	
	Option 1	Option 2	Option 3	Option 4	Option 5
Technical Characteristics					
Interceptor Speed at Burnout (Kilometers per second)	6	8	10	4	6
Interceptor Peak Acceleration (g)	22	27	39	15	35
Kill-Vehicle Mass (Kilograms)	140	30	30	140	30
Total Interceptor Mass (Kilograms)	3,088	3,469	17,160	847	442
Cost (Billions of 2004 dollars)					
Research and Development	7-10	9-13	13-20	7-10	9-13
Initial Production	3-4	4-5	6-7	16-22	5-7
Operations Over 20 Years	6-10	6-10	6-10	33-46	13-20
Total	16-24	18-28	25-37	56-78	27-40
Operational Effectiveness					
Able to Counter Liquid-Fuel ICBMs	Yes	Yes	Yes	Yes	Yes
Able to Counter Solid-Fuel ICBMs					
From a small country	Yes	Yes	Yes	No	No
From a large country	No	Yes	Yes	No	No
Additional Cost to Counter Solid-Fuel ICBMs[a] (Billions of 2004 dollars)	n.a.	0	0	107-146	30-40
Vulnerable to Denial of Basing Access	Yes	Yes	Yes	No	No
Has Potential for Worldwide Coverage	No	No	No	Yes	Yes

Source: Congressional Budget Office.

Note: ICBM = intercontinental ballistic missile; n.a. = not applicable.

a. From a country the size of Iran (in the case of Options 1 through 3) or countries between 25 and 45 degrees of both north and south latitude (in the case of Options 4 and 5).

of achieving the additional interceptor speed could result in a longer development time for this alternative than for Option 2, given the same rate of investment spending.

Options 4 and 5: Space-Based Interceptors

CBO's last two alternatives consist of constellations of SBIs in low-Earth orbit. Both constellations are sized to defend against liquid-fuel ICBMs launched from locations between 25 degrees north latitude (southern Iran) and 45 degrees north latitude (northern North Korea). Both would also provide a two-shot engagement for increased probability of a successful intercept.

Although the two systems offer similar effectiveness, they achieve that effectiveness with different combinations of interceptor performance and constellation size. In terms of interceptor performance, Option 4 is on the low end with a speed of 4 km/sec and peak acceleration of 15g. The interceptors in Option 5 have a speed of 6 km/sec and peak acceleration of 35g. Because of its faster interceptors, the constellation in Option 5 can be much smaller than the one in Option 4: 156 SBIs (with a total launch mass of about 83 metric tons) compared with 368 satellites (and a total launch mass of 468 metric tons) for Option 4.[11] Since the effectiveness of the BPI systems is similar at both interceptor speeds, the decision about

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[11] The combinations of system characteristics in those options are not among the ones shown in Summary Figure 3.

which option is more cost-effective could hinge on future launch costs.

An additional difference between the two space-based systems is the mass of each kill vehicle: 140 kg in Option 4 and 30 kg in Option 5. As noted earlier, additional research and development would be needed to produce a kill vehicle as light as 30 kg, which means that the system in Option 5 might take longer to develop and field than the one in Option 4, given the same rate of investment spending.

Comparison of Capability Under Different Alternatives

All of the alternative BPI systems described above are able to provide full coverage against liquid-fuel ICBMs from Iran and North Korea, but they do not have identical capabilities. Each design has inherent advantages and disadvantages in such matters as cost, potential area of coverage, capability against solid-fuel ICBMs, dependence on access to foreign bases, vulnerability to being attacked or to exhausting their supply of interceptors, and strategic responsiveness. Not surprisingly, the greatest differences exist between the space-based systems and the surface-based ones.

Costs

Developing and fielding the surface-based BPI system in Option 1 and then operating it for 20 years would cost a total of $16 billion to $24 billion (in 2004 dollars), CBO estimates. The system in Option 2 would cost $18 billion to $28 billion, and the one in Option 3 would cost $25 billion to $37 billion (see Summary Table 2). Those ranges reflect the possibility of cost growth comparable to what similar defense programs have experienced in the past.

The cost estimates for the three surface-based systems assume procurement of equipment for 10 BPI launch sites. Each site would include six interceptors plus a set of communications and battle management equipment. Using two interceptor shots per engagement, each launch site could engage three targets with that allotment of interceptors. For those options, 10 sites' worth of equipment would be enough to defend against liquid-fuel ICBMs fired from Iran and North Korea and also provide some equipment for use against other countries of concern. Additionally, the estimate for each surface-based system includes costs to purchase, operate, and maintain three cargo ships on which a BPI site could be located to provide sea-based capability (such as against North Korea).

Of the space-based systems, the one in Option 5 would cost $27 billion to $40 billion (similar to the high-performance surface-based system in Option 3). The lower-speed SBI system in Option 4 would cost more—$56 billion to $78 billion—because of higher costs per interceptor and higher launch costs to put more mass into orbit. The space-based options are more expensive than the surface-based options because they need more interceptors to cover Iran and North Korea at all times and because they require paying for launch services. The high operations costs for those options reflect the need to periodically buy and launch replacement SBIs. CBO assumes that each interceptor in orbit would have a life span of seven years—a typical length for satellites in low-Earth orbit—compared with at least 20 years for a surface-based interceptor.

The costs of the various BPI systems would be lower if planners accepted less capability. For example, five surface sites could provide coverage just of Iran and North Korea (with nothing left over for testing or other coverage). The cost of that capability over 20 years could be as low as $14 billion to $21 billion for Option 1, $16 billion to $26 billion for Option 2, and $22 billion to $35 billion for Option 3, CBO estimates. Similarly, if the space-based systems used a single shot against each ICBM, the cost of Option 4 could drop to $36 billion to $51 billion and the cost of Option 5 could decline to $20 billion to $31 billion. Although those less-capable systems would probably be considered insufficient as a stand-alone defense, they might be adequate as complements to other layers of a multilayer ballistic missile defense system.

Areas of the World Covered

The space-based systems in Options 4 and 5 would provide much greater global coverage than the surface-based systems would. Those SBI constellations could fully cover the surface of the Earth between 25 and 45 degrees of both north and south latitude—a total area of about 145 million square kilometers. In principle, an SBI constellation could be designed to provide full global coverage, but at far greater cost than for Options 4 and 5. Of course, much of the area that would be covered in those options does not need coverage. Proponents of basing interceptors in space, however, argue that a space-based BPI capability offers a hedge against uncertainty about the identity and nature of future threats.

The surface-based systems in Options 1 through 3, by contrast, would cover only the countries near which they were deployed. North Korea and Iran, for example, total an area of about 1.8 million square kilometers. Defending against liquid-fuel ICBMs launched from those countries would use five of the 10 sets of equipment purchased in Option 1 and three of the 10 purchased in Options 2 and 3.

Capability and Cost to Counter Solid-Fuel ICBMs

The challenge to BPI systems will be greater if threat nations can develop or acquire more-advanced ICBMs, such as solid-fuel types, that have shorter boost phases. Against a representative solid-fuel ICBM, Option 1 would provide coverage only of smaller countries and then only if favorable basing locations were available and commit times were short. For instance, Option 1 could cover relatively small North Korea only if commit times could be held to less than 45 seconds or if several launch sites could be located in China.

Greater interceptor speeds would give Options 2 and 3 better performance against ICBMs with short burn times. CBO estimates that even with commit times longer than 60 seconds, both options could provide full coverage from a single site in the Sea of Japan against a solid-fuel ICBM with a three-minute burn time fired from North Korea. Against larger countries, the greater interceptor speed of Option 3 has the potential to provide full coverage with fewer sites than in Option 2. With a 60-second commit time, Option 3 could cover Iran using four launch sites, whereas seven sites would be needed for Option 2. Costs would not rise for that additional capability, because the 10 sites' worth of equipment purchased under the surface-based options would be adequate to provide coverage against solid-fuel ICBMs from both North Korea and Iran. However, fewer systems would be available for other scenarios.

The space-based interceptors used in Options 4 and 5 could also provide coverage against solid-fuel ICBMs—but only if the number of interceptors in the constellations more than tripled. Because the footprint of each SBI would be smaller against a target with a shorter burn time, Option 5 would need a constellation of 516 satellites, and Option 4 would require 1,308 satellites. Those extra SBIs would add about $30 billion to $40 billion to the cost of Option 5 and $107 billion to $146 billion to the cost of Option 4, CBO estimates.

Reliance on Access to Foreign Basing

The ability to position surface-based BPI systems where necessary will always be subject to geopolitical constraints. In general, the fewer launch sites a surface-based system needs to counter a threat, the less vulnerable it will be to other countries' denial of access to basing sites. Thus, of the surface-based alternatives, Option 3 is the least vulnerable to denial of basing access because it is the most capable, requiring the fewest sites to counter a potential threat. Option 2 and Option 1 follow, in that order.

A higher-speed surface-based system is generally less subject to basing constraints, but actual differences will depend on the specific scenario. In the case of North Korea, all three options would need only one launch site in international waters, so none would be vulnerable to denied access. In the case of Iran, Option 1's additional vulnerability could be more significant than the simple need for additional sites. The 8-km/sec and 10-km/sec interceptors in Options 2 and 3, respectively, would provide coverage against liquid-fuel ICBMs from sites in Afghanistan and Iraq, where access to basing might be available (at least when this report was written). The additional sites that Option 1, with its 6-km/sec interceptors, would need would be in places such as Turkmenistan or Azerbaijan, where access is less assured.

By operating in space, the systems in Options 4 and 5 would be free from the problem of access to basing.

Vulnerability of the BPI System to Attack

Besides limitations on their location, another way in which BPI systems could be prevented from fulfilling their mission is if they were attacked by the threat country they were covering. CBO's analysis assumed that all surface-based BPI systems would be located about 100 km from the border of the threat country—out of range of artillery or unguided rockets. However, the sites might still require their own defenses against short-range missiles or attack aircraft from that country. (The costs of those defenses are not included in CBO's cost estimates.) Space-based systems, for their part, would be potentially vulnerable to antisatellite weapons, should threat countries develop such weapons.

Ability to Defeat Increasing Numbers of ICBMs

If threat countries had multiple ICBMs—or decoys, such as first-stage rockets with dummy upper stages, that might draw interceptor fire—their simultaneous launch could saturate the defenses of a BPI system. Additional interceptors could help counter that capability.

CBO's options allow for six interceptors per surface site or two SBIs over a threat area at all times. Six surface-based interceptors are enough to engage three targets, and two SBIs are enough to engage one target, under the assumption of two-shot salvo tactics. However, the number of those targets that could be engaged at the same time would depend on how many interceptors in flight a site could simultaneously guide.

The number of interceptors needed to engage additional ICBMs (or decoys) grows in proportion to the number of launch sites needed to defend against the first target. Options 2 and 3 would need the fewest additional interceptors because they would require the fewest sites. Options 4 and 5 would require many additional space-based interceptors to defeat increasing numbers of ICBMs because additional interceptors would be needed throughout the entire constellation to counter multiple simultaneous launches. If the threat ICBMs were not launched simultaneously, however, other SBIs in orbit—which would move into position over the threat in about 10 minutes during the normal course of their orbits—could be fired.

Strategic Responsiveness

In terms of reacting quickly to a "bolt from the blue" type of attack, Options 4 and 5 would be the most responsive against threats that arose between 25 and 45 degrees of latitude. Once in orbit, their interceptors would always be deployed and on alert. In contrast, the surface-based systems would require time for interceptors to be deployed to forward locations on the perimeter of a threat country. However, if a threat arose outside the 25- to 45-degree latitude bands, moving surface-based interceptors might be faster than expanding an SBI constellation by launching more satellites into orbit.

Among the surface-based systems, those in Options 1 and 2 would be more responsive than the one in Option 3 because their interceptors could be deployed more easily by air. Even with a very light kill vehicle, a 10-km/sec interceptor would weigh more than 17,000 kg. Only one interceptor could be mounted on each launch vehicle that would be transportable by a C-17 aircraft, increasing the number of transport flights needed for each BPI site. In addition, interceptors of that size are best suited to basing in fixed silos (as is the case for the Ground-Based Midcourse Defense system that MDA plans to locate in Alaska and California). Although such silos are practical on home territory, permanent BPI installations in foreign countries would be likely to pose greater access problems than mobile BPI systems.

Sea-based BPI sites could be less responsive than land-based ones because ships have longer transit time than aircraft do. That difference could be lessened if the BPI ships were prepositioned in forward areas or if a land-based site could be flown in and temporarily placed on a local ship until the dedicated BPI ship arrived.

CHAPTER

1

Ballistic Missile Defenses and Threats

Possible attack by ballistic missiles has been a concern to U.S. military planners ever since Germany struck Great Britain with V-2 rockets 60 years ago. Unlike powered cruise missiles (such as the Tomahawk) or winged glide missiles (such as the Joint Standoff Weapon), ballistic missiles are unpowered and unassisted by aerodynamic lift forces for most of their trajectory. Much as a fly ball in baseball is only under power while it is in contact with the bat, a pure ballistic missile is only under power while its booster burns at the beginning of its flight.[1] Nevertheless, intercontinental ballistic missiles (ICBMs) can travel more than 10,000 kilometers (6,000 miles).

Ballistic missiles' flight can be divided into distinct phases:

- The boost phase, from launch until the missile's booster burns out;
- The midcourse phase, as the warhead coasts toward its target;[2] and
- The terminal phase, the warhead's final descent to its target.

In the past, U.S. work on missile defenses has focused mainly on the midcourse and terminal phases. But today, efforts to defend against ballistic missiles emphasize building layered defenses, with each layer targeting missiles in a different phase of their flight. Thus, interest has grown in developing systems to intercept ICBMs in the boost phase, during the first few minutes after they are launched.

A Brief History of U.S. Ballistic Missile Defenses

Efforts to defend against attacks by ballistic missile are nearly as old as ballistic missiles themselves. As early as 1945, for example, the Army's Project Thumper (which sought to develop a high-altitude defense against aircraft) examined how Allied forces could defend against Germany's new V-2 rockets. (Project reports concluded that such defenses were beyond the capability of existing technology.) By the time the Soviet Union deployed its first intercontinental ballistic missiles in 1960, the Army, Navy, and Air Force were pursuing a variety of ballistic missile defense (BMD) programs. Much of that research was consolidated in Project Defender under the newly established Advanced Research Projects Agency. In 1962, President Kennedy assigned Project Defender to the highest category of national priorities for research and development.[3]

Throughout the 1960s and early 1970s, BMD efforts progressed amid debate about their technical feasibility, their affordability, and whether ballistic missile defense fit into the nation's strategic defense posture. The Army's first BMD program, called Nike-Zeus, went through sev-

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[1] Some advanced ballistic missiles have delivery buses that provide additional maneuvering power later in the missile's trajectory. However, that power is usually intended to fine-tune the warhead's aim or to complicate missile defense efforts rather than to contribute substantially to the missile's flight.

[2] The initial portion of the midcourse phase, after the missile's booster burns out but before the warhead is deployed, is sometimes considered a separate phase, known as ascent or early ascent. In early ascent, although the ICBM is no longer actually burning, the large, hot (relative to the warhead) booster body is still present for defensive systems to track.

[3] The White House, National Security Action Memorandum No. 191, October 1, 1962.

eral iterations: Nike-X, Sentinel, and finally Safeguard, a system that was briefly operational in 1976 to defend the ICBM fields at Grand Forks Air Force Base in North Dakota. That deployment complied with a 1974 protocol to the Anti-Ballistic Missile (ABM) Treaty, which limited ballistic missile defenses to a single fixed site for defending either the national capital or an ICBM field.

After the ABM treaty was ratified in 1972, the United States expended little effort on developing ballistic missile defenses until the early 1980s, when concern grew about a Soviet first-strike capability that might be able to attack both U.S. strategic forces and most metropolitan areas in the United States. In 1983, the Joint Chiefs of Staff recommended that the United States put more emphasis on strategic missile defense. Soon after, the Strategic Defense Initiative Organization was established to pursue an expanded program of missile defense research.

Earlier BMD systems such as Safeguard relied on nuclear warheads to destroy incoming ICBMs. By the early 1980s, however, technological improvements in sensors, guidance systems, boosters, and command-and-control systems had revived interest in “hit to kill,” a concept that had been explored by Project Defender as early as 1960. A hit-to-kill interceptor is itself a missile. But instead of having an explosive warhead, it uses precise homing to fly a “kill vehicle” into a target (akin to a bullet hitting a bullet). Relative velocities at impact can reach many kilometers per second, which means that the kinetic energy of such a collision can be much greater than the chemical energy of a similarly sized explosive warhead. The feasibility of hit to kill was demonstrated in 1984 by the Army’s Homing Overlay Experiment when a kill vehicle launched from Kwajalein Atoll in the Pacific intercepted a dummy ICBM warhead launched from Vandenberg Air Force Base in California.

The Strategic Defense Initiative was originally focused on defending against a large-scale Soviet attack, so concepts for BMD systems included large numbers of interceptors. For example, scientists and engineers at Lawrence Livermore National Laboratory proposed a constellation of small, smart, space-based interceptors—called Brilliant Pebbles—that were intended to destroy target ICBMs during their boost phase. By attacking an ICBM in that phase, before its multiple independently targeted reentry vehicles could be deployed, a single Brilliant Pebbles interceptor could potentially destroy as many as 10 Soviet warheads. Although early concepts to defend against worst-case scenarios envisioned deploying as many as 100,000 Brilliant Pebbles, later estimates were reduced to around 7,000.[4]

The end of the Cold War brought fundamental changes in the rationale for a strategic missile defense system. The focus shifted from countering a large-scale Soviet attack to two other objectives: defending the United States against accidental or limited ICBM strikes and defending deployed U.S. forces against attacks by theater (shorter-range) ballistic missiles. Some defense planners argued that limited strikes against the United States could be a threat if rogue elements in the former Soviet Union seized control of strategic nuclear systems or if ICBM technology proliferated to other hostile countries. The threat posed to deployed forces by theater ballistic missiles was demonstrated during Operation Desert Storm when an Iraqi Scud missile killed 28 soldiers in Al Khobar, Saudi Arabia.

In 1991, lawmakers enacted the Missile Defense Act, which defined the goal of deploying a system to defend against limited attacks by ballistic missiles while still complying with the ABM treaty. With that treaty’s restriction on developing defenses against ICBMs, and in the wake of the Scud attacks during Desert Storm, BMD efforts focused on developing theater-level defenses against missiles in their terminal phase. Those efforts resulted in systems such as Patriot Advanced Capability-3 (or PAC-3) and the Theater High-Altitude Air Defense (known as THAAD).[5] Those systems were permitted under a 1997 agreement among the parties to the ABM treaty because they lacked the performance necessary to defeat long-range ballistic missiles.

By the mid-1990s, intelligence estimates of threats to the United States prompted greater interest in national missile defense (NMD). The Department of Defense announced a program in 1996 that called for three years of development of an NMD system and then—if the system’s components had been tested successfully and threats to the United States warranted its use—three more years to deploy an operational system. That system

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[4] D.R. Baucom, “The Rise and Fall of Brilliant Pebbles” (paper presented at the North Carolina First Flight Centennial Commission International Flight Symposium, “They Taught the World to Fly: The Wright Brothers and the Age of Flight,” October 23, 2001).

[5] The “T” in THAAD has recently been changed from “Theater” to “Terminal.”

Table 1-1.

Implications of Intercepting Ballistic Missiles During Different Phases of Their Flight

Phase	Advantages	Disadvantages
Boost	Missile's thermal signature is large Booster is large physical target One interceptor can destroy multiple warheads Decoys are difficult to deploy	Time available for intercept is short (about three to five minutes) Interceptor must be positioned close to country from which missile is launched Rocket plume can obscure the missile's body Missile's acceleration complicates the tracking solution Hitting the booster can leave a live warhead that falls short of its target
Ascent/Early Ascent	Missile is still large and hot Extends the time available for intercept One interceptor can destroy multiple warheads Missile is probably flying a predictable ballistic trajectory	Warhead separation on the missile being targeted may be very rapid Interceptor must be positioned close to country from which missile is launched Interceptor must destroy warhead because warhead has enough speed to reach its target
Midcourse	Longest time is available for intercept Missile is probably flying a predictable ballistic trajectory Defenses can be positioned in North America or on the oceans	Missile's thermal signature is small, making it difficult to detect and track Warhead is small physical target Decoys can dilute defenses
Terminal	Most decoys are stripped away during atmospheric reentry Forward deployment is unnecessary	Time available for intercept is very short Debris from the intercept may fall on defended territory

Source: Congressional Budget Office.

as envisioned in the late 1990s would have included a new tracking radar and 20 midcourse interceptors based in Alaska, upgrades to existing missile defense radars, space-based sensors, and a command-and-control system. Officials recognized that pursuing that system would eventually require additional modifications to or withdrawal from the ABM treaty. However, in September 2000, President Clinton decided against deploying an NMD system.

The Bush Administration subsequently withdrew the United States from the ABM treaty and broadened BMD efforts to develop and deploy integrated systems to defend against ballistic missiles of all ranges in all phases of flight. To meet that goal, the Missile Defense Agency (MDA) is working on a variety of sensors, weapons, and command-and-control infrastructure that will be integrated into a layered ballistic missile defense system (BMDS).

Layered Defenses and Boost-Phase Intercept

Defending against ballistic missile attacks is a challenging technical undertaking. In the case of ICBMs, a defensive system may need to hit a warhead smaller than an oil drum that is traveling above the atmosphere at speeds greater than 13,000 miles per hour. Countermeasures such as decoy warheads that may be carried by ICBMs further complicate the problem of intercepting targets. To achieve a high probability of destroying ballistic missiles in flight, MDA is pursuing a layered defensive approach. Each layer is designed to exploit the particular vulnerabilities and overcome the particular challenges that a ballistic missile presents during a phase of its flight: boost phase, midcourse phase, or terminal phase (see Table 1-1). Layered defenses are built on the premise that although technological limitations might keep any one layer from having an adequate chance of successfully in-

Table 1-2.

Funding for the Missile Defense Agency's Ballistic Missile Defense System Interceptors Program, 2004 to 2009

(Billions of 2004 dollars)

	2004	2005	2006	2007	2008	2009	Total, 2004-2009
Budget for BMDS Interceptors Program	0.1	0.5	1.1	1.6	2.0	2.2	7.6
Total MDA Budget	7.6	9.0	8.3	9.6	7.9	7.9	50.3
Memorandum:							
BMDS Interceptors as a Percentage of MDA's Budget	1.5	5.6	12.9	16.8	25.5	27.8	15.2

Source: Congressional Budget Office based on a briefing by staff of the Missile Defense Agency, March 4, 2004.

tercepting its target, multiple layers could together provide an effective defense.

For the past several years, midcourse intercept has been the primary focus of efforts to defend the United States against attack by ICBMs. The Department of Defense plans to field the initial elements of a midcourse defense by the end of 2004, including the Ground-Based Midcourse Defense system and portions of the sea-based Aegis BMD system. Boost-phase and terminal-phase efforts —such as the Airborne Laser and THAAD, respectively—have focused more on shorter-range ballistic missiles, such as Scuds.

Recently, however, MDA initiated a new effort to develop hit-to-kill interceptors capable of engaging ICBMs in the boost phase. Interest in boost-phase intercept of ICBMs dates to the 1950s, when the Air Force's Ballistic Missile Boost Intercept program looked at using a system of space-based interceptors to deploy large wire-mesh structures that would destroy ICBMs in the boost phase. The Brilliant Pebbles and Global Protection Against Limited Strikes programs of the late 1980s and early 1990s were also primarily envisioned as boost-phase intercept (BPI) systems.

The previous focus on space-based BPI was necessitated by the large size of the Soviet Union. Only an orbiting platform would have access to the interior of that country, the area from which ICBMs would be launched. Because today's concerns center around smaller countries, attention has shifted to terrestrial BPI systems—either land-based, sea-based, or airborne—that could be deployed to the borders of a nation considered a threat. Such systems have become a potentially attractive means of providing a boost-phase defense layer against ICBMs fired at the United States. In December 2003, MDA awarded a contract to Northrop Grumman to develop an initial (or Block 10) surface-based BPI system.

MDA's five-year budget plan envisions that funding for kinetic-energy boost- and ascent-phase intercept systems—currently called BMDS Interceptors—will grow from $118 million in 2004 to $511 million in 2005 and reach nearly $2.2 billion by 2009 (see Table 1-2). Although the BMDS Interceptors program accounts for only about 6 percent of MDA's proposed 2005 budget, that share grows to nearly 28 percent by 2009. Over the 2004-2009 period, that program averages 15 percent of the agency's budget, or a total of about $7.6 billion. Most of the program's current funding is focused on mobile terrestrial systems, although about $10 million of the 2005 budget request is slated for initial analysis of a space-based system. Through 2009, MDA plans to allocate a total of about $700 million for work on a space-based BPI system.

Characteristics of ICBMs Important for BPI

A ballistic missile is composed of a guidance system and one or more warheads mounted on a rocket booster. To achieve intercontinental range—approximately 10,000 kilometers (km) or more—ICBM boosters typically accelerate their payloads to a speed of about 6 to 7 km per second.

Table 1-3.

Nations with Long-Range Ballistic Missiles

	Longest Range (Kilometers)	Built or Bought
China	10,000+	Built
France	4,500	Built
India	2,500	Built
Iran	1,200	Built
Israel	3,000	Built
Libya[a]	700	Bought
North Korea	2,000	Built
Pakistan	2,300	Built
Russia	10,000+	Built
Saudi Arabia	2,500	Bought
Syria	700	Built
United Kingdom	10,000+	Bought
United States	10,000+	Built

Source: Congressional Budget Office based on Duncan Lennox, ed., *Jane's Strategic Weapons Systems*, vol. 39 (Coulsdon, Surrey: Jane's Information Group, July 2003).

Note: The countries listed above all have missiles with ranges greater than 500 kilometers.

a. As part of its recent rapprochement with the United States and the United Kingdom, Libya has indicated that it will give up its missiles that have ranges greater than 300 kilometers.

Boosters can be grouped into two types: liquid-fuel and solid-fuel. Liquid-fuel boosters are the older and simpler technology. A liquid propellant and a liquid oxidizer are used to fuel the missile's rocket motor. Although liquid-fuel missiles are easier to build than solid-fuel missiles, they require complicated and potentially dangerous fuel-handling activities and thus can be more difficult to operate and maintain.

Solid-fuel boosters use a propellant and an oxidizer that are molded into a solid motor core with a binding agent. The solid-fuel motor, which is ignited in its hollow interior and burns from the inside out, generates thrust by expelling the combustion products from its nozzle. Producing large solid-fuel boosters is challenging both technologically and industrially, but such boosters are relatively easy to handle after production.

The type of booster used in an ICBM is particularly important to designers of boost-phase intercept systems. Solid-fuel ICBMs usually have shorter boost phases than liquid-fuel ICBMs do. Thus, a BPI system designed to counter solid-fuel ICBMs will need higher performance because its interceptors will have less time to reach their targets. (Performance requirements for BPI systems are discussed in Chapter 2.)

Representative Threats for Comparing BPI Systems

As many as 35 countries are thought to possess ballistic missiles, although only 13 of them have missiles with ranges greater than 500 kilometers (see Table 1-3). Just four nations—China, Russia, the United States, and the United Kingdom—are known to possess ICBMs.[6] But other countries, including some that have had less-than-friendly relations with the United States over the years, are believed to be pursuing ICBM capability. For example, North Korea and Iran could have such capability by 2015, according to the December 2001 National Intelligence Estimate.[7] Specific intelligence estimates are subject to debate, but if a nation is developing space-launch capability, it is in effect gaining the ability to field ICBMs. Both North Korea and Iran have said they plan to develop space-launch systems.[8]

To compare the effectiveness of alternative designs for BPI systems, this analysis uses North Korea and Iran as representative threats. North Korea is believed to be developing two long-range ballistic missiles—the Taep'o-dong 1 SLV (space-launch vehicle), with a range of about 5,000 km, and the Taep'o-dong 2, with a range of about 6,000 km, according to unclassified estimates (see Table 1-4).[9] In August 1998, North Korea launched a Taep'o-dong 1 SLV with the stated goal of orbiting a small test satellite. Although the launch was unsuccessful, it clearly demonstrated North Korea's pursuit of long-range-missile capability. Iran has Shahab 3 missiles with an estimated

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[6] The United Kingdom's long-range ballistic missiles are submarine-launched Tridents and hence are technically considered submarine-launched ballistic missiles (SLBMs) rather than ICBMs.

[7] National Intelligence Council, *Unclassified Summary of a National Intelligence Estimate: Foreign Missile Developments and the Ballistic Missile Threat Through 2015* (December 2001).

[8] Duncan Lennox, ed., *Jane's Strategic Weapons Systems*, vol. 39 (Coulsdon, Surrey: Jane's Information Group, July 2003), p. 122.

[9] Ibid., pp. 121-123.

Table 1-4.

Characteristics of North Korean and Iranian Ballistic Missiles and of Representative ICBMs

Missile Type	Number of Booster Stages	Booster Fuel	Launch Weight (Kilograms)	Length (Meters)	Range (Kilometers)	Estimated Status
North Korean and Iranian Ballistic Missiles						
North Korea						
Taep'o-dong 1	2	Liquid	21,700	27.0	2,000	Flight testing[a]
Taep'o-dong 1 SLV	3	Liquid (2 stages) Solid (1 stage)	25,700	32.0	5,000	Flight testing[a]
Taep'o-dong 2	2	Liquid	64,000	35.0	6,000	In development
Iran						
Shahab 3	1	Liquid	16,250	16.0	1,300	Operational
Shahab 4	1	Liquid	42,000	22.8	2,000	In development
Representative ICBMs						
Former Soviet Union						
SS-17	2	Liquid	71,100	20.9	11,000	Fielded in 1975
SS-25	3	Solid	45,100	20.5	10,500	Fielded in 1988
United States						
Titan II	2	Liquid	149,700	31.3	15,000	Fielded in 1963
Minuteman III	3	Solid	34,500	18.2	13,000	Fielded in 1970

Source: Congressional Budget Office based on Duncan Lennox, ed., *Jane's Strategic Weapons Systems*, vol. 39 (Coulsdon, Surrey: Jane's Information Group, July 2003).

Note: ICBMs = intercontinental ballistic missiles; SLV = space-launch vehicle.

a. Only one Taep'o-dong 1 (an SLV version) is known to have been tested. However, additional missiles are thought to be available, either for operational use or for additional testing.

range of about 1,300 km. It is thought to be developing a Shahab 4 with a range of about 2,000 km.[10]

Those North Korean and Iranian ballistic missiles have much longer ranges than do tactical ballistic missiles, such as the Scud. But their ranges fall far short of the more than 10,000 km distance typical of ICBMs that have been fielded in the past (see Table 1-4).

Besides the characteristics of missiles that might be targeted, geography is an important factor with respect to the performance needed from a BPI system. Iran and North Korea are also good representative threats for assessing the implications of geography. Surface-based BPI interceptors must fly farther to reach ICBMs fired from the interior of large countries and thus usually need higher speeds if deployed against such countries. Iran is the world's 16th largest country by area, so it provides a case study that could stress surface-based systems. Geography plays a role in space-based systems as well. Orbital dynamics require that the higher the latitude of the country to be covered, the more interceptors must be deployed. A space-based system with orbits that provided coverage of North Korea (the northern tip of which is located above 42 degrees latitude) could cover about 75 percent of the world's countries—and about 90 percent of the countries that, at least currently, might be considered potentially hostile to the United States.

The next chapter assesses the performance characteristics that a BPI system would need to defend the United States against ICBMs fired from those two representative countries. Chapter 3 examines alternative BPI designs that would meet the needed performance, and Chapter 4 compares each alternative's strengths, weaknesses, and costs.

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[10] Ibid., pp. 97-98.

CHAPTER

2

Performance Needed for an Operationally Effective BPI System

A kinetic-energy boost-phase intercept consists of a series of events that culminate with a kill vehicle (basically a self-guided, nonexplosive warhead) hitting and destroying a target ballistic missile. Those events can be divided into two stages (see Figure 2-1):

- The *commit stage,* which lasts from when a threat missile is launched until a BPI interceptor is fired. Functions in the commit stage include detecting the target, tracking it, and deciding to fire (that is, committing an interceptor to the engagement).
- The *interceptor flyout stage*, which lasts from when the interceptor is launched until it reaches (and, if all goes well, destroys) its target.

The challenge of BPI is the short time available for the engagement. Both the commit and flyout stages must be executed while the threat missile is in its boost phase. Typically, that phase lasts four to five minutes for a liquid-fuel intercontinental ballistic missile and only about three minutes for a solid-fuel ICBM.

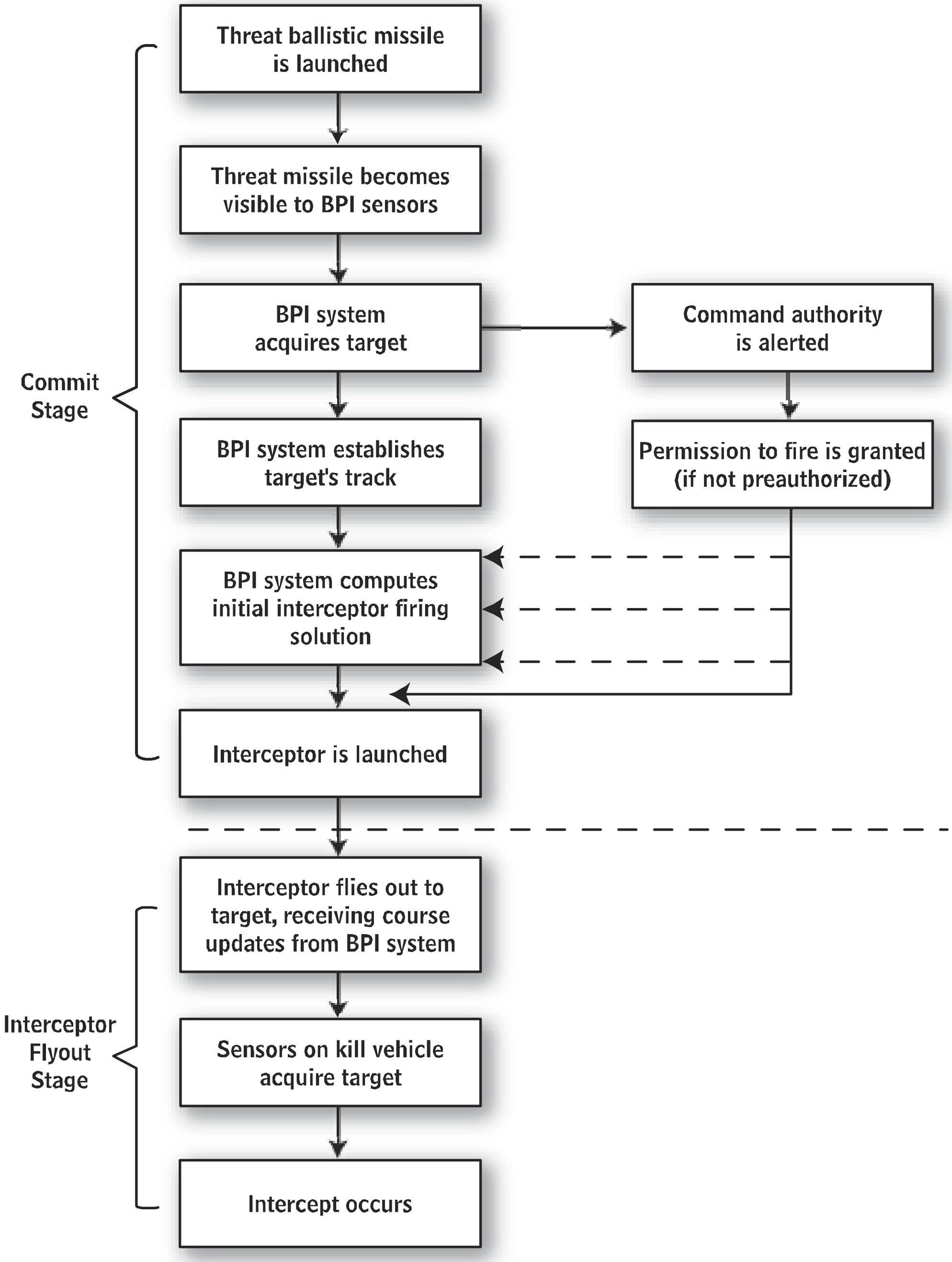
More time may be available for the engagement if the BPI sensors can continue tracking the target into its early-ascent phase (after the booster burns out but before the warheads separate from the rest of the missile). How much time can be gained depends on the design of the specific ICBM being targeted. Early ascent may last on the order of 60 seconds, but it can be much shorter with ICBMs designed to deploy their warheads early. Because of those uncertainties, the engagement times used in this study could represent early ascent as well as boost. For simplicity, however, intercepts are referred to as occurring no later than “at booster burnout.” If the intercept occurs in the early-ascent phase, the kill vehicle must be able to selectively hit and destroy an ICBM warhead (as opposed to the missile as a whole) because the warhead will already have enough velocity to reach its target.

For this analysis, the Congressional Budget Office assessed the capability of potential BPI systems against representative liquid-fuel ICBMs (a lower-technology threat) and solid-fuel ICBMs (a more advanced threat). The representative liquid-fuel ICBM has a burn time of about five minutes, similar to that of U.S. Titan II or Russian SS-12 missiles of the 1960s. The representative solid-fuel ICBM has a burn time of about three minutes, making it comparable to current U.S. Minuteman III or Russian SS-25 missiles.

The burn time of an ICBM’s booster, coupled with the distance that an interceptor must travel to reach its target (which results from the geography of a particular scenario), determines the response time and interceptor speed necessary for a BPI system. In general, more technologically advanced ICBMs require higher-performance BPI systems because those ICBMs usually have shorter burn times and faster acceleration. Defending against larger threat countries also requires higher-performance surface-based BPI systems because interceptors will have to fly farther to reach ICBMs launched from deep inside a country. Locating surface-based BPI systems in the general path that a threat ICBM might fly to reach the United States can ease performance needs by allowing better geometry for the engagement.

Figure 2-1.

Series of Events in a Boost-Phase Intercept

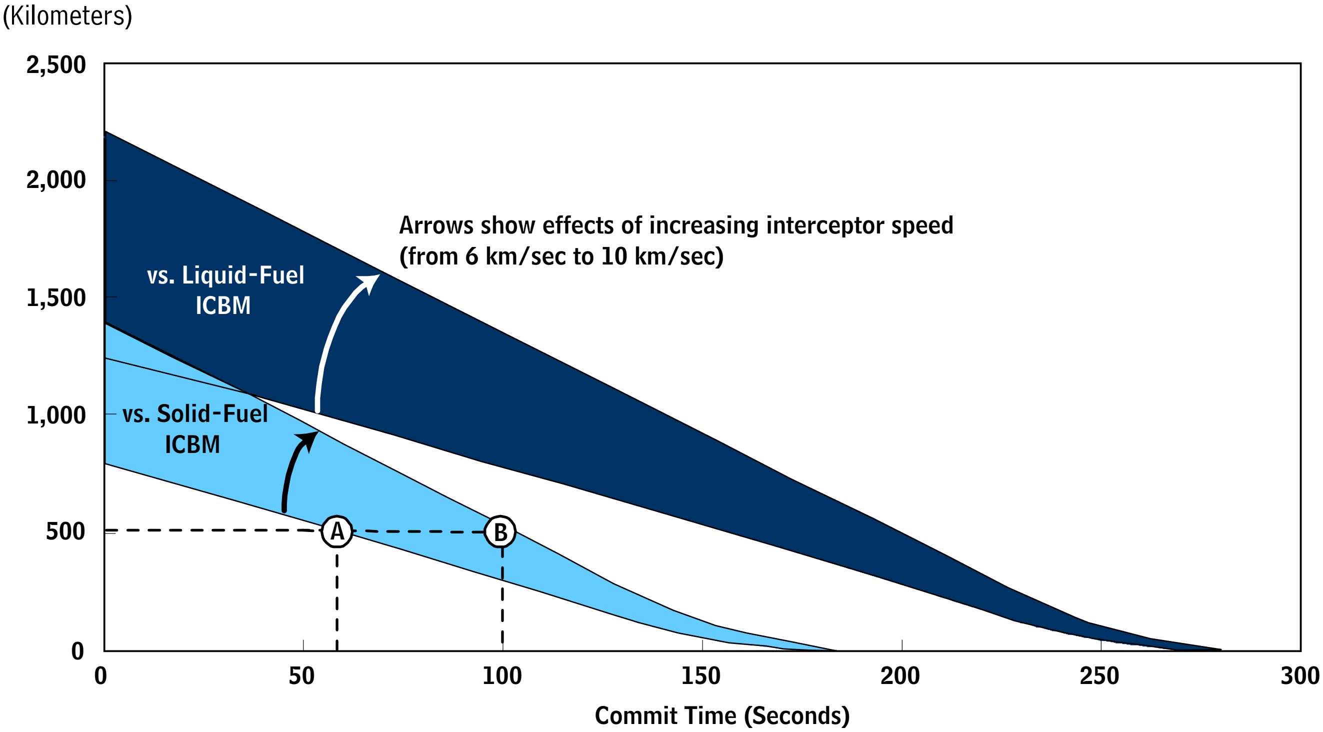


Source: Congressional Budget Office.

Note: BPI = boost-phase intercept.

Figure 2-2.

Interceptor Reach Versus Commit Time for Interceptor Speeds Between 6 km/sec and 10 km/sec



Source: Congressional Budget Office.

Notes: The figure assumes that interceptors have a burn time of 60 seconds.

ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

The performance of space-based systems is less sensitive to those geographic factors. Nevertheless, geography—in particular, the latitudes of threat countries to be covered—is an important factor in determining the number of space-based interceptors needed in a defensive system.

Commit Time, Interceptor Speed, and Location

A system's ability to meet short BPI timelines hinges on its having some combination of a fast commit time, high interceptor acceleration and speed, and launchers that can be positioned close to potential threats. Different combinations of those characteristics can yield systems with similar overall effectiveness.

The first two characteristics—commit time and interceptor speed—can be varied to provide a particular interceptor reach (the maximum distance from its launcher that an interceptor can travel in the available engagement time). Interceptor reach determines the coverage area provided by a BPI system. For a given commit time, faster interceptors will provide greater reach. Likewise, for a given interceptor speed, shorter commit times will provide greater reach. For example, a BPI system with 6-kilometer/second interceptors and a 60-second commit time could provide a reach of about 500 km against a solid-fuel ICBM (see point A in Figure 2-2). If the system had a 100-second commit time, a 10-km/sec interceptor would be needed to provide the same reach (point B in the figure). For a given commit time and interceptor speed, the interceptor reach is greater against liquid-fuel ICBMs than against solid-fuel ICBMs because the liquid-fuel missiles burn longer and thus allow more time for an intercept.

The interceptor reach needed for a given scenario depends in turn on the ability to position launchers in advantageous places. This study analyzes the interactions between those BPI characteristics to determine how a

Table 2-1.

Characteristics of Radar and Infrared Sensors

Sensor Location	Radar	Infrared Sensors
Surface (Land or ship)	Detection delays because of horizon limits are likely to be too long for all but the smallest threat countries Cloud cover does not affect detection Access to necessary locations could be constrained Technology is easy to deploy and maintain	Detection delays because of horizon limits are likely to be too long for all but the smallest threat countries Sensors are not useful for tracking if they are located beneath clouds
Airborne	Horizon is greater than with surface radar Cloud cover does not affect detection Access to necessary locations could be constrained Several aircraft per orbit are needed for around-the-clock coverage Stratospheric airship platforms may lack enough power for operations	Horizon is greater than with surface radar Need for high-altitude position limits the choice of platform to high-altitude unmanned aerial vehicles or stratospheric airships Several aircraft per orbit are needed for around-the-clock coverage High-altitude airships operating for long periods are unproven
Space	Horizon is not limited if enough satellites are in orbit Cloud cover does not affect detection Access is not constrained Technology is unproven and could be expensive to deploy	Horizon is not limited if enough satellites are in orbit Cloud cover can delay detection Access is not constrained Some strategic warning constellation (representing a sunk cost) will be required with or without boost-phase intercept Technology must have tracking capability

Source: Congressional Budget Office.

range of performances would translate into operational effectiveness in the context of actual engagement geometries.

The length of the commit stage is primarily a function of the defense's sensors and battle management components. The length of the flyout stage depends mainly on interceptor speed and launcher position relative to the ICBM's launch point and trajectory. Speed and acceleration are functions of an interceptor's design. The ability to put launchers in appropriate locations hinges on the mobility of the system and access to basing in other countries, in the case of surface-based BPI systems, and on the separation between satellites, in the case of space-based interceptors.

Sensors and Battle Management Components

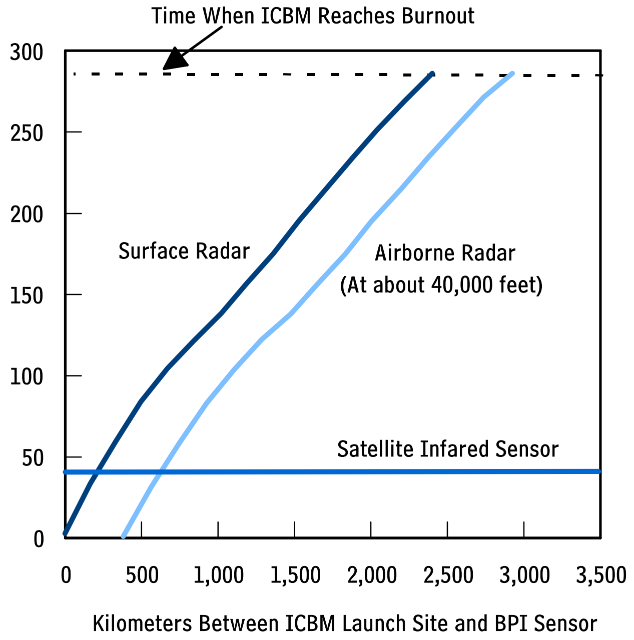
The timeline of the commit stage for a boost-phase intercept consists of the time to detect a threat ICBM, the time to establish tracking, and the decision time before an interceptor is launched. Radar that detects the body of an ICBM or infrared sensors that detect the hot plume of the booster can be used to acquire the target in its boost phase. Either type of sensor might be located on the surface (land or ship), on an aircraft, or on a satellite. Each type and location of sensor entails advantages and disadvantages when used to detect ballistic missiles (see Table 2-1).

Satellite-based sensors are usually preferred for detecting ballistic missiles because satellites in high orbits do not have their view (or horizon) limited by the curvature of the Earth to the extent that lower sensors do. Horizon limits can cause significant delays in detecting ICBMs. For example, to detect a liquid-fuel ICBM within 60 seconds of its launch, a surface radar would have to be within about 300 km of the launch site if the missile's trajectory was straight over the sensor (see Figure 2-3). The delay would be longer if—as would almost certainly be the case—the trajectory did not pass directly over the sensor. Airborne radar can allow for detection from farther away—up to about 800 km within the same 60-second time frame—because its altitude gives it an expanded horizon. Infrared sensors on a constellation of satellites

Figure 2-3.

Time Needed for a BPI Sensor to Detect a Notional Liquid-Fuel ICBM

(Seconds)



Source: Congressional Budget Office.

Notes: In the case of surface and airborne radar, detection is affected by horizon limits caused by the curvature of the Earth. In the case of infrared sensors on satellites, detection may be affected by cloud cover, which hides the ICBM from view until it breaks through the clouds. These data are for ICBM trajectories straight over the surface and airborne sensors.

BPI = boost-phase intercept; ICBM = intercontinental ballistic missile.

would offer the fastest detection: delays of no more than 30 to 45 seconds, and then only if cloud cover above the ICBM launch site hid the missile from view until it broke through the clouds (at an altitude of around 7 km). "See-to-ground" sensors located in orbit might avoid the cloud-cover delay suffered by infrared sensors, but such technology is unproven.

As described later in this chapter, a BPI system that is effective under a broad range of operational conditions will need a commit time of about 60 seconds. Surface sensors farther than 400 km from the launch site of a liquid-fuel ICBM or 550 km from the launch site of a solid-fuel ICBM cannot meet that timeline. Surface radars could be effective against small countries such as North Korea, but an ICBM launched from the interior of a large country such as Iran might not be visible to a surface radar for more than two minutes—a significant delay given BPI engagement times of three to six minutes (including potential ascent-phase engagements).

Both infrared and radar can be used for the second commit-stage function: establishing the track of the target ICBM in order to guide an interceptor to the missile. Both types of sensors establish a track by taking successive snapshots of the target and determining its change in position as a function of time. That information is used to calculate where the ICBM is heading and hence where the interceptor should be aimed (a process known as finding a tracking and firing solution). Radar is excellent for that task because it can take rapid snapshots of the target to provide a high-resolution track. Moreover, since radar is an active sensor, a single site can establish range to the target.[1] Although radar is ideal, an infrared sensor should be able to track an ICBM in the boost phase if the sensor is designed to take snapshots quickly enough to rapidly establish a track and if there are enough sensors that at least two can see the target to determine its range.

Once a track is established, the BPI system must calculate an aim point for the interceptor and then receive permission to fire. Given the short timelines involved, it is likely that the BPI system will have to operate automatically. Even if time was available, little additional information could be provided to assist a human operator with the decision to launch or hold fire. Rather, the decision would have to be made in advance as part of an engagement doctrine (for example, stating that if a ballistic missile is launched from within a given area, it will be assumed to pose a threat and will be engaged). Delegating to a computer the authority to fire a missile at an airborne target over a foreign country is an important policy issue involved in fielding a BPI system.

The total commit times that a system ultimately achieves will depend on the performance of the sensors, the speed with which the system's tracking algorithms can generate a tracking and firing solution from the sensors' data, and

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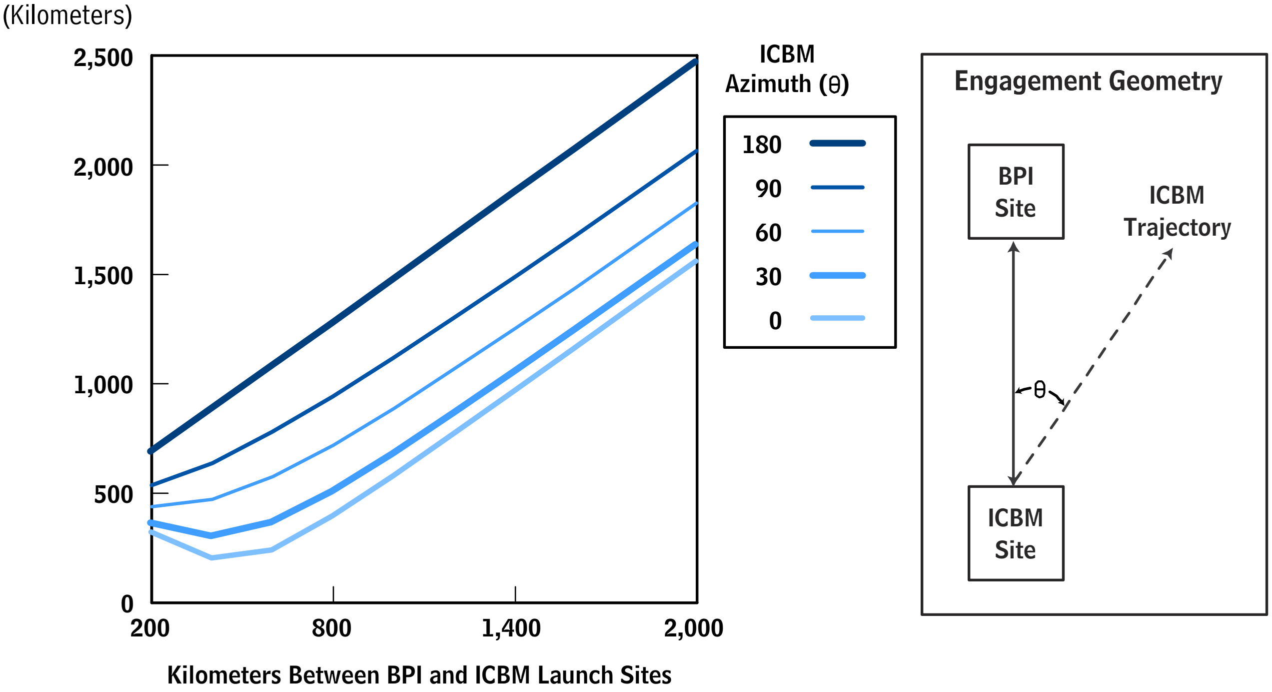
1. Active sensors such as radar generate pulses of energy that are transmitted toward the target. The radar determines range by measuring the time required for reflected energy to return from the target. Passive sensors such as infrared arrays detect energy emitted by the target itself. Determining range with passive sensors usually requires triangulation with multiple sensors, although a general knowledge of the target's trajectory can be used to provide a rough estimate of range from a single sensor.

Figure 2-4.

Interceptor Reach Needed Against a Notional Solid-Fuel ICBM, by ICBM Trajectory



Source: Congressional Budget Office.

Notes: These data assume that intercept occurs when the ICBM reaches burnout.

BPI = boost-phase intercept; ICBM = intercontinental ballistic missile.

the amount of decision delay (if any) inherent in the engagement doctrine. With space-based infrared sensors, commit times could probably be on the order of 60 seconds, assuming no decision delay. The 60-second window would include 30 to 45 seconds for the ICBM to break through any cloud cover plus 15 to 30 seconds to establish a tracking and firing solution. Earlier detection would be possible if the ICBM was launched on a clear day (a clear night is actually the most favorable for infrared sensors) or if space-based see-to-ground sensors such as radar were available to penetrate any cloud cover.

Even near-instantaneous detection might not shorten the commit time significantly, however, because obtaining a tracking solution requires that the ICBM start to pitch over and commit itself to a down-range direction. Very early in flight, an ICBM is primarily moving upward rather than down range. For example, after 30 seconds, the notional liquid-fuel ICBM described at the beginning of this chapter has reached an altitude of about 3 km but has only traveled about 0.6 km down range. If a BPI interceptor is committed too soon, it may be vulnerable to evasive maneuvers by the ICBM, which are easier to implement earlier in a missile's flight.

Interceptors

After the commit stage, the remaining time before the ICBM's booster burns out is available for the interceptor to fly out to its target. The ability of the interceptor to reach its target in time depends on its speed and acceleration, the relative locations from which the ICBM and the interceptor were launched, and the trajectory that the ICBM follows. However, surface-based and space-based interceptors differ in the way in which they depend on those factors.

Surface-Based Interceptors

How great a reach a surface-based interceptor needs against a particular type of ICBM is determined by the initial separation between the ICBM and interceptor launch sites and the ICBM's direction, or azimuth (θ), relative to the line between those sites (see Figure 2-4). For example, if the launcher for a representative solid-fuel ICBM (with a three-minute burn time) and a BPI launcher were 1,000 km apart, the interceptor would need a reach of about 600 km if the ICBM was fired directly over the BPI site ($\theta = 0$ in the figure). The required reach would double to about 1,200 km if the ICBM's azimuth was perpendicular to the line between the launchers ($\theta = 90$ in the figure).

For a given surface-based BPI site, a threat country will contain potential ICBM launch locations that span a range of launcher separation distances and ICBM azimuths. Because of Iran's large size, a BPI system to defend against missile launches from that country would need greater reach in the time available than a system covering smaller North Korea. A BPI system based in Iraq to defend against Iranian solid-fuel ICBMs would need a maximum interceptor reach of more than 2,000 km (the highest point of the shaded area in Figure 2-5), compared with a maximum of about 700 km for a BPI system based in the Sea of Japan to defend against North Korean solid-fuel ICBMs.

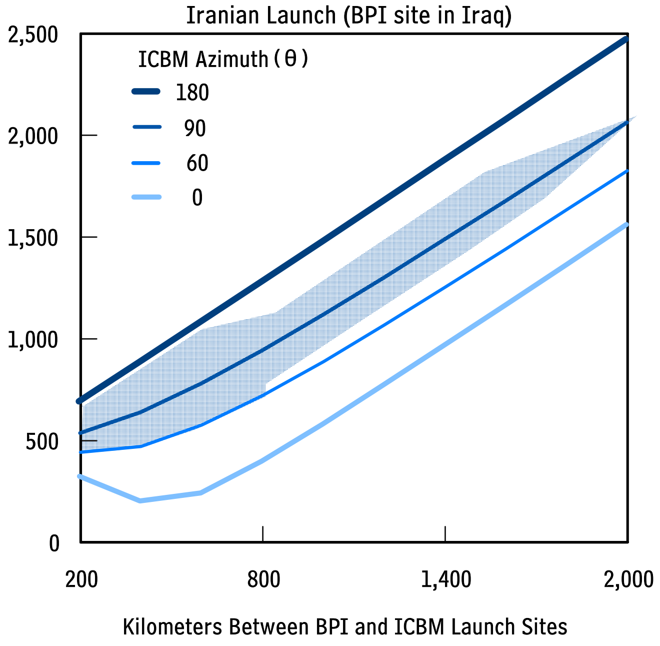
Once an interceptor has been committed, its reach depends on its speed and acceleration. With the same maximum speed, a missile that accelerates more quickly will have greater reach than one that accelerates more slowly because it will attain its top speed after a shorter booster burn time. The discussion that follows assumes burn times of 60 seconds for surface-based interceptors. (The design implications resulting from higher or lower accelerations are discussed in Chapter 3.)

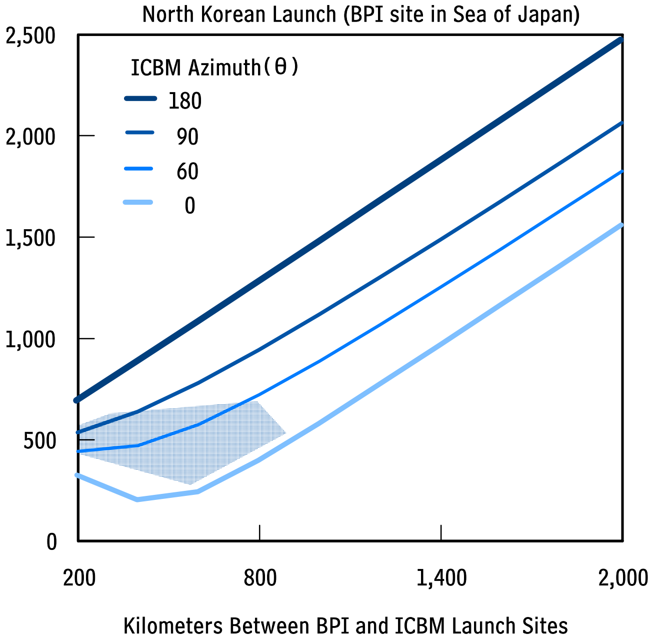
A useful measure of the effectiveness of a BPI system is the *coverage* it provides against a threat country. In this analysis, an area within a threat country is considered to be covered by a BPI system if the system is capable of engaging an ICBM fired from that area toward any location in the United States (including Alaska and Hawaii). As described above, the coverage of a BPI system varies with the length of time it takes to commit and the speed of its interceptors (see Figure 2-6). For an illustrative case that involved using a single BPI site in eastern Iraq to intercept an Iranian liquid-fuel ICBM, the contours in the first panel of Figure 2-6 represent the coverage area possible with various commit times, ranging from zero (no delay) to 120 seconds, assuming an interceptor speed of 8 km per second. The no-delay contour, which offers the greatest coverage, corresponds to simultaneous launch of

Figure 2-5.

Interceptor Reach Needed Against a Solid-Fuel ICBM Launched from Iran or North Korea

(Kilometers)





Source: Congressional Budget Office.

Notes: Shaded areas indicate the range of potential engagement conditions for each country. These data assume that intercept occurs when the ICBM reaches burnout.

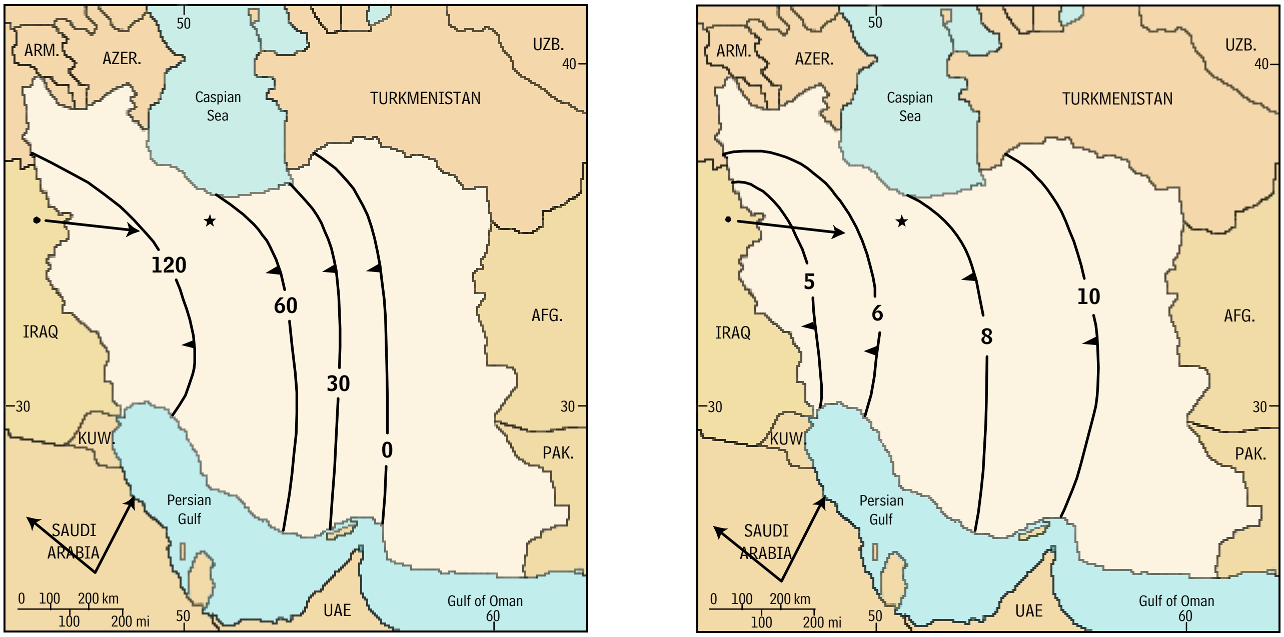
BPI = boost-phase intercept; ICBM = intercontinental ballistic missile.

Figure 2-6.

Impact of Commit Time and Interceptor Speed on BPI Coverage of Iran from a Site in Iraq

Impact of Commit Time (Assuming 8-km/sec interceptor)

Impact of Interceptor Speed (Assuming 60-sec commit time)



Source: Congressional Budget Office.

Notes: Contour lines show the limits of launch areas that could be defended for the BPI commit times (in seconds) or interceptor speeds (in kilometers per second) shown. The arrows in the bottom lefthand corners indicate the spread of trajectories at which an Iranian liquid-fuel ICBM could be launched against the United States. The dot in Iraq indicates the notional BPI site. These figures assume a BPI system intended to defend the entire United States, with an interceptor burn time of 60 seconds.

BPI = boost-phase intercept; ICBM = intercontinental ballistic missile.

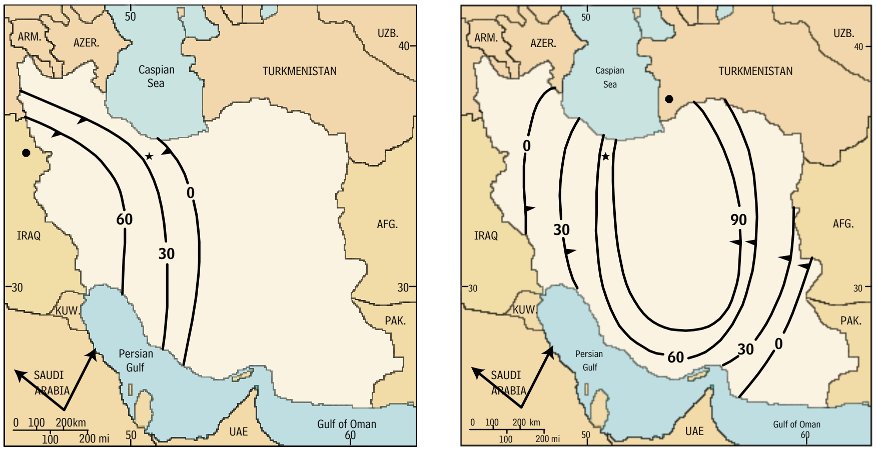
the ICBM and the interceptor—a theoretical lower bound that could not be achieved in practice. As the commit time increases, the area covered by a given BPI site decreases.

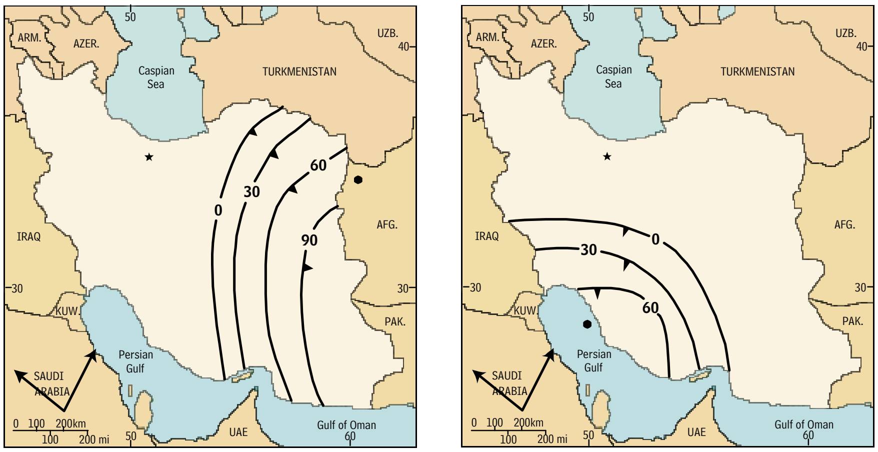
The second panel of Figure 2-6 shows the effects of varying interceptor speed rather than commit time. The contours represent the coverage limits for interceptor speeds ranging from 5 km/sec to 10 km/sec, given a commit time of 60 seconds. The coverage offered by a BPI system decreases dramatically below interceptor speeds of 6 km/sec, primarily because ICBMs reach speeds of 6 to 7 km/sec as they near burnout, and an interceptor moving much more slowly than its target can only hit that target under a narrow set of favorable engagement conditions.

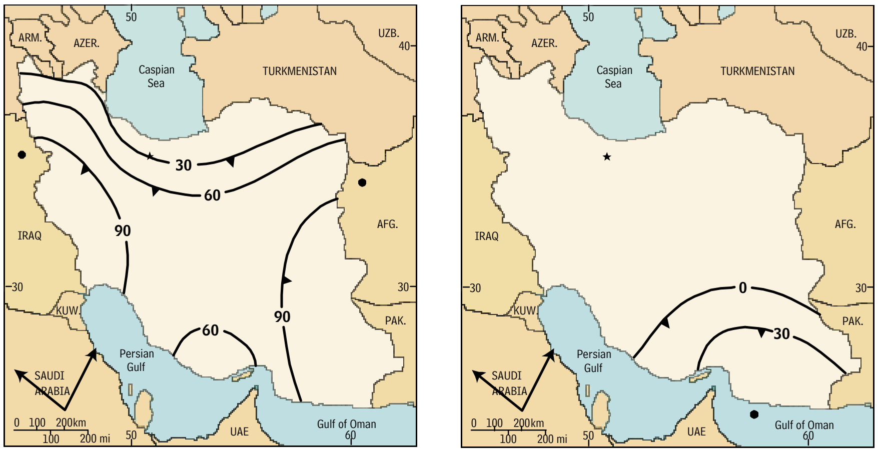
Covering a country the size of Iran would be difficult with a single surface BPI site and modest system performance. Even with the ideal of no commit time, a single site with 8-km/sec interceptors could not cover all launch locations in the country. However, multiple sites could operate together to provide greater coverage (see Figure 2-7). In fact, the whole coverage offered by multiple sites could be greater than the sum of the individual coverages. For example, a particular ICBM launch location in Iran might not be covered by a BPI site to its east (such as in Afghanistan) for missiles shot toward the west, nor would it be covered by a BPI site to its west (such as in Iraq) for missiles shot toward the east. But between them, both of those BPI sites might cover such a location. One drawback of a multiple-site approach, however, is that it would require greater reliance on access to foreign bases.

Figure 2-7.

Coverage of Iran Possible from BPI Sites in Different Locations


Iraq Site Turkmenistan Site


Afghanistan Site Ship in Persian Gulf


Afghanistan and Iraq Sites Ship in Gulf of Oman

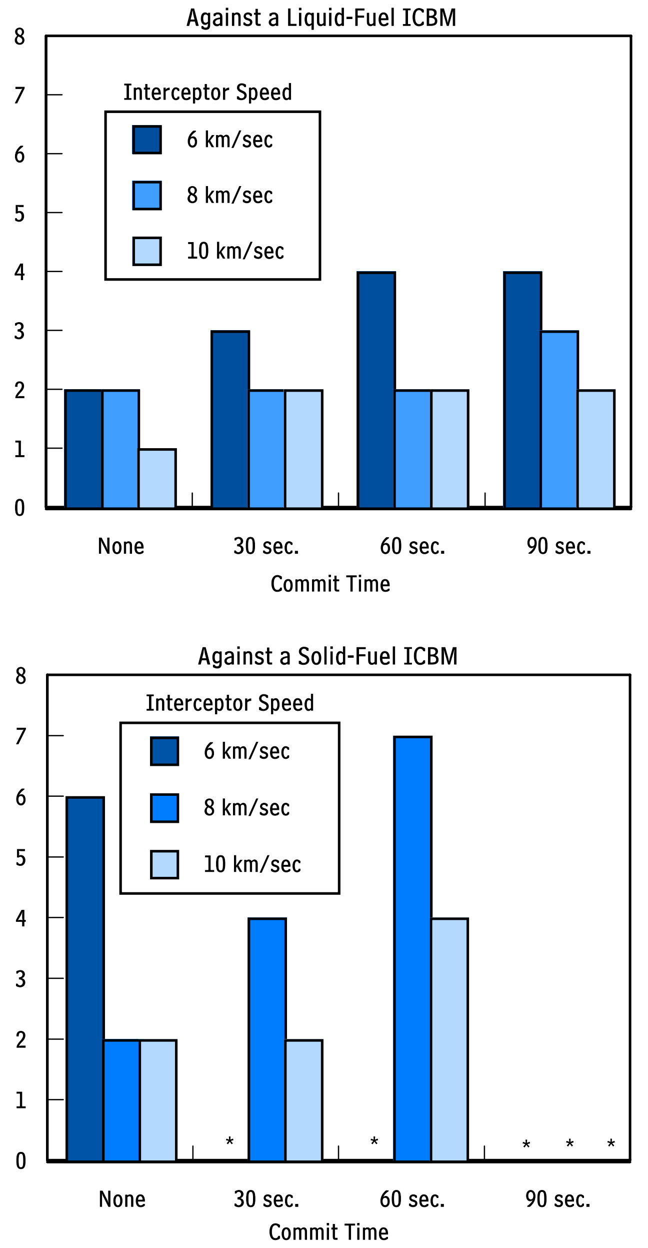
Source: Congressional Budget Office.

Notes: Contour lines show the limits of launch areas that could be defended for the BPI commit times (in kilometers per second) shown. The arrows in the bottom lefthand corners indicate the spread of trajectories at which an Iranian liquid-fuel ICBM could be launched against the United States. The dots indicate notional BPI sites. These figures assume a BPI system intended to defend the entire United States, with an interceptor burn time of 60 seconds and an interceptor speed of 6 kilometers per second.

BPI = boost-phase intercept; ICBM = intercontinental ballistic missile.

Figure 2-8.

Number of Surface-Based BPI Sites Needed for Full Coverage of Iran, by Commit Time and Interceptor Speed



Source: Congressional Budget Office.

Notes: The figures assume that interceptors have a burn time of 60 seconds.

* = full coverage not possible; BPI = boost-phase intercept; ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

Two to four BPI sites would be necessary to fully defend against liquid-fuel ICBMs launched from all possible Iranian locations, given commit times between 30 and 90 seconds and interceptor speeds between 6 and 10 km/sec (see Figure 2-8). With no commit delay, one site with 10-km/sec interceptors could cover Iran, but no commit delay implies advance knowledge of the exact location, time, and direction of the ICBM launch. With that level of information, a cruise missile strike on the launcher could be a better defensive measure.

In the case of Iranian solid-fuel ICBMs, a greater number of surface sites would be needed to provide full coverage (see Figure 2-8). Even with short commit times (below 30 seconds), a system with 6-km/sec interceptors would require many sites to fully cover Iran. Coverage would be better with 8-km/sec interceptors, although the number of sites needed would climb rapidly with increasing commit time. Even with very fast interceptors (10 km/sec), the system would require four sites if the commit time was 60 seconds.

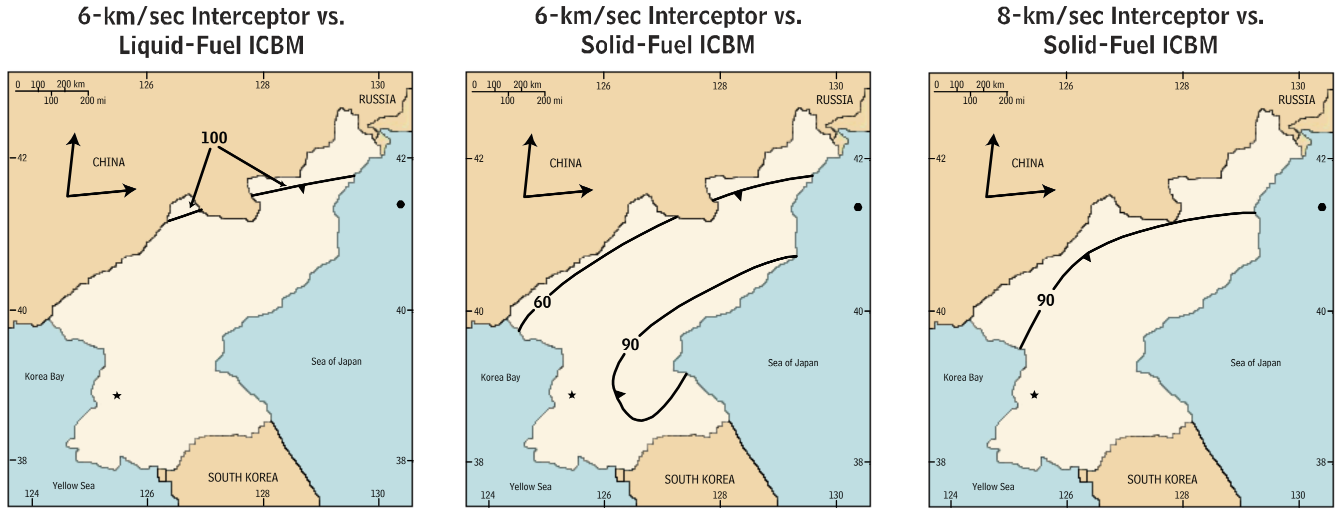
The effectiveness of a surface-based BPI system could be much greater in the case of North Korea because of the shorter distances involved. A system firing 6-km/sec interceptors from a single site (a ship in the Sea of Japan) could provide full coverage against North Korean liquid-fuel ICBMs given a 90-second commit time (see Figure 2-9). That system could provide full coverage against solid-fuel ICBMs from North Korea if the commit time could be reduced to about 45 seconds. With faster interceptors—say, 8 km/sec—commit times against solid-fuel ICBMs could lengthen to about 75 seconds and still allow for full coverage.

Space-Based Interceptors

The coverage provided by a BPI system using space-based interceptors (SBIs) is also driven by commit time, interceptor speed, and interceptor acceleration. But various additional factors that do not come into play for surface-based systems help determine that coverage as well. For example, because an entire SBI system will have to be put into orbit, minimizing its weight—and hence its launch costs—is an important consideration. In addition, although orbiting interceptors are free from constraints on foreign basing, their locations are still limited by the laws of orbital dynamics.

Figure 2-9.

Impact of Commit Time and Interceptor Speed on BPI Coverage of North Korea from a Site in the Sea of Japan



(Full coverage at 90-second commit time)

(Full coverage at 30-second commit time)

(Full coverage at 60-second commit time)

Source: Congressional Budget Office.

Notes: Contour lines show the limits of launch areas that could be defended for the BPI commit times (in seconds) shown. The arrows in the upper lefthand corners indicate the spread of trajectories at which a North Korean ICBM could be launched against the United States. The dot in the Sea of Japan indicates the notional BPI site.

BPI = boost-phase intercept; ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

An SBI system would most likely consist of a constellation of interceptor satellites located in low-Earth orbit at an altitude of about 300 km. Satellites in higher-altitude orbits would require greater launch costs and be farther from their intended targets. As with surface-based BPI systems, that additional distance would result in the need for faster, heavier interceptors. However, maintaining lower orbits for long periods of time would require extra fuel to periodically counter atmospheric drag, and that additional fuel would also result in greater weight and launch costs.

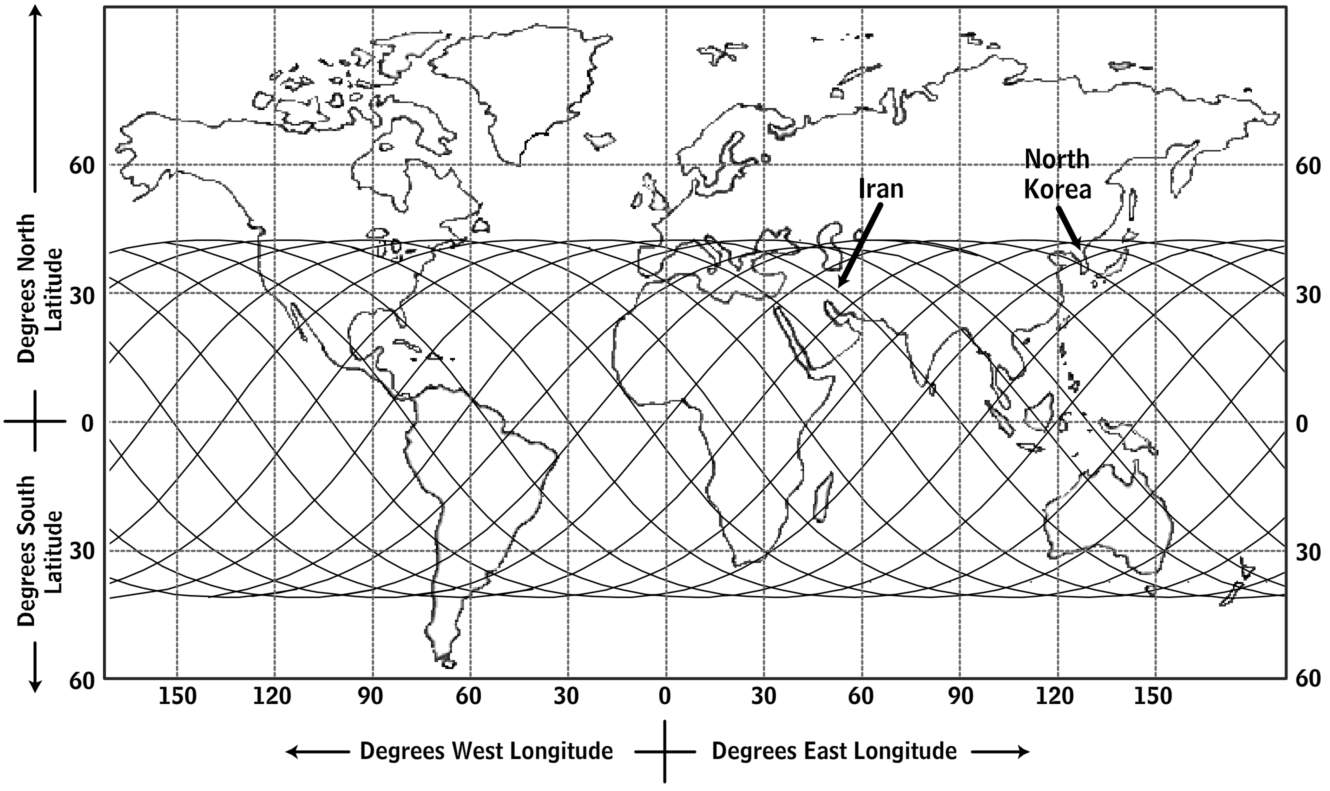
Objects in low-Earth orbit are not stationary over one point on the Earth. Rather, their location travels a sinusoidal ground track that is centered at the equator (see Figure 2-10). The inclination of the orbit measures how far north and south of the equator the orbital path reaches. The ground track of each successive orbit is shifted because of the Earth's rotation. Over a 24-hour period, a low-altitude satellite in a 45-degree inclined orbit will generate 16 ground tracks between 45 degrees north latitude and 45 degrees south latitude. As an SBI travels in its orbit, it can defend against ICBM launches that may occur within its footprint.

Because of that orbital behavior, space-based boost-phase intercept capability cannot be concentrated against specific threats—any single SBI will spend most of its time out of position, either over the ocean or over other countries. Providing full coverage of a particular threat country requires having a constellation of SBIs with their orbits positioned such that one or more interceptors is over the threat area at any given time. The orbital inclination used for the satellites is determined by the highest-latitude threat area that needs to be covered.

The number of SBIs that a system requires depends on the type of threat ICBM, the performance of the system's components, and the lowest-latitude threat area to be covered. As in surface-based BPI systems, the first two factors determine the reach of each interceptor, which in turn determines the maximum spacing between SBIs. The lowest latitude to be covered is important because SBIs in inclined orbits do not provide equal coverage at

Figure 2-10.

Ground Track of a Satellite in a 45-Degree Inclined Low-Earth Orbit



Source: Congressional Budget Office.

all latitudes. The sinusoidal ground track associated with low-Earth orbit means that each satellite spends a greater amount of time at latitudes approaching the orbital inclination and less time at lower latitudes. For example, a constellation of satellites in a 45-degree inclined orbit that had enough SBIs to fully cover North Korea—which lies between 38 degrees and 45 degrees north latitude—could have gaps in its coverage as much as 40 percent of the time for the southern regions of Iran, at about 25 degrees north latitude.[2] (That estimate assumes that the space-based system has a 60-second commit time and interceptors with 4-km/sec speed and 40 seconds of burn time.)

The gaps in coverage of Iran could be filled by adding SBIs to the constellation, essentially decreasing the spacing between each interceptor. That approach would have the advantage of providing extra coverage of North Korea—an average of two SBIs at any given time. Alternatively, additional SBIs could be launched into lower-inclination orbits better tailored to Iran's latitudes. That approach might require fewer SBIs but would not provide the benefit of greater coverage of North Korea.

Just as surface-based systems with higher interceptor speed and acceleration would tend to require fewer sites because of the interceptors' greater reach, SBIs with higher speed and acceleration would result in the need for fewer interceptors because each one would have a larger footprint. The number of satellites needed to provide full coverage against liquid-fuel ICBMs launched from between 25 and 45 degrees north latitude—a band that encompasses Iran and North Korea—would vary from about 70 to more than 900 for the various combinations of commit time and interceptor speed that the Congressional Budget Office analyzed (see Figure 2-11). (The design implications of different SBI speeds and accelerations are discussed in the next chapter.)

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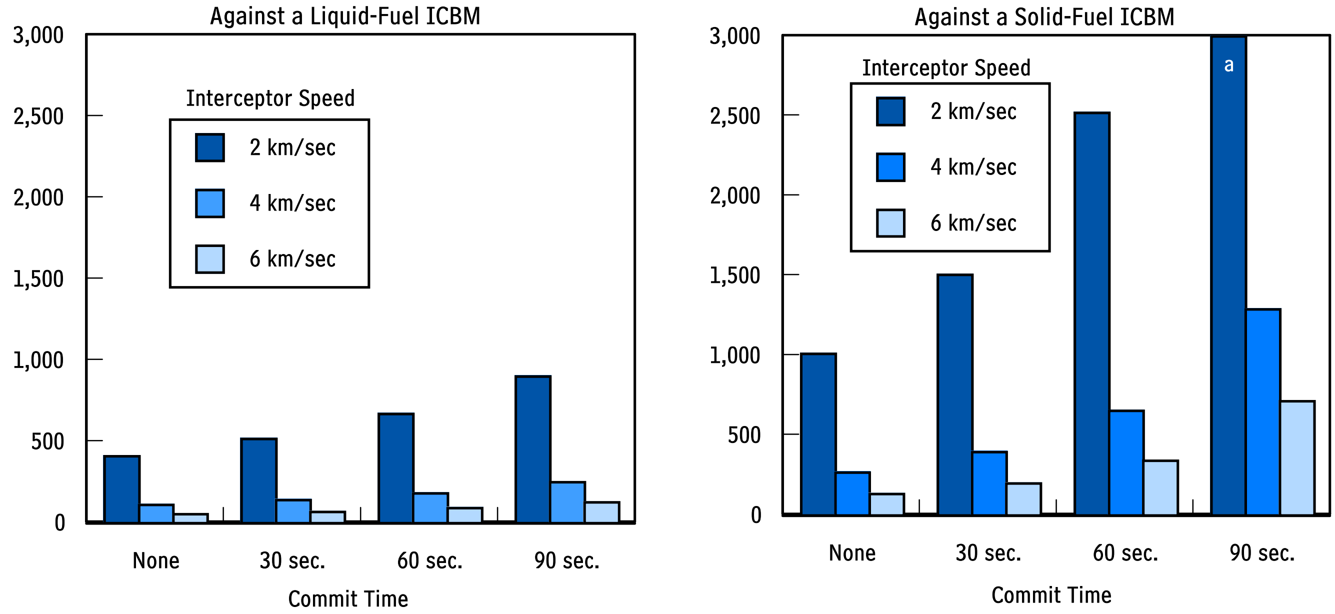
[2] The northernmost point in North Korea actually lies at about 43 degrees north latitude. However, intercepts of North Korean ICBMs fired toward the continental United States would have to occur farther north.

Figure 2-11.

Number of SBIs Needed for Full Coverage of North Korea and Iran, by Commit Time and Interceptor Speed



Source: Congressional Budget Office.

Notes: The figures assume that interceptors have an acceleration of 10g, that kill vehicles have a mass of 30 kilograms, and that the life jacket accounts for 50 percent of an SBI's total mass. They also assume that the threat country does not fire more than one ICBM at the same time and that a single interceptor is shot at an ICBM (which is why these numbers differ from the ones shown in Summary Figures 3 and 4).

SBI = space-based interceptor; ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

a. Actual number of SBIs is 5,455.

Solid-fuel ICBMs would present a greater challenge to a space-based BPI system, just as they would to a surface-based system. The shorter burn time of solid-fuel boosters effectively reduces the footprint of each space-based interceptor. Consequently, the spacing between SBIs must be reduced, increasing the size of the constellation. The number of satellites needed to defend against a solid-fuel ICBM launched from the aforementioned latitude band would be several times greater than the number necessary with a liquid-fuel ICBM (see Figure 2-11).

CHAPTER

3

Alternative Designs for BPI Systems

An operational boost-phase intercept system will consist of sensors to detect and track target ballistic missiles and interceptors to engage them. Battle management and communications equipment will also be necessary to calculate tracking and firing solutions, serve as the link between sensors and interceptors, and tie the BPI system in with other elements of a layered ballistic missile defense system. The previous chapter illustrated how a broad range of sensor and interceptor performance could be combined to yield systems capable of engaging intercontinental ballistic missiles in their boost phase.

Any specific system design will not only have operational strengths and weaknesses compared with other designs but also require different levels of investment for development, procurement, and operation. To compare the potential cost and effectiveness of different approaches to BPI, the Congressional Budget Office (CBO) developed five alternative system designs that span a range of performance levels and basing options. This chapter describes the technical analyses underlying each BPI alternative, three of which are surface-based and two of which are space-based. Chapter 4 compares the options' potential costs and capabilities from several different operational perspectives.

Each design was structured to be able to counter a liquid-fuel ICBM fired from any location in North Korea or Iran at any target in the United States. CBO chose those countries because of their geographic characteristics and because many observers consider them to pose the most likely ballistic missile threats to the United States. As described in Chapter 1, both nations are developing long-range missiles based on liquid-fuel technology and both are believed to possess weapons of mass destruction. CBO designed each BPI system to be able to defeat ICBMs fired from anywhere in North Korea or Iran because that ability means that the system could not be easily circumvented by mobile ICBM launchers. Although the alternative systems are intended to counter liquid-fuel ICBMs, the analysis also compares their abilities to counter solid-fuel ICBMs.

Assumptions About Sensors and Battle Management Components

The sensors and battle management components of a BPI system determine the commit time that can be achieved. As Chapter 2 indicated, a system that is effective against ICBMs will most likely need commit times of less than 90 seconds—and preferably no more than 60 seconds. To defend against ICBM launches from deep inside a large country, such as Iran, sensors would have to be based in space to meet that time constraint. However, a BPI system would probably not require its own constellation of sensor satellites. Instead, it could rely on elements of the sensor architecture that is already being developed for the multilayer ballistic missile defense system and for other purposes. (Current infrared sensors on satellites offer detection capability, but they generally lack the worldwide capability to track targets for the BPI mission.)

For boost-phase intercept, the most relevant BMDS sensors are part of the Space-Based Infrared System (SBIRS) now in development. That system, commonly known as SBIRS-High, is expected to include a mix of four satellites in geosynchronous orbit (remaining stationary over one point on the Earth) and two sensor payloads on other satellites in highly elliptical orbits. The improved capability that the new sensors are expected to offer will broaden the set of missions that can be accomplished. For this study, CBO assumed that the necessary elements of SBIRS would be available as planned to support the BPI mission. Because those sensor systems are common to all of the BPI options, they are not explicitly included in comparisons of the options' costs and effectiveness.

Besides sensors, a BPI system requires a communications architecture to transmit detection and tracking information to the surface BPI sites or in-orbit SBIs in preparation for launching interceptors. Having a direct link between the BMDS sensors and each BPI site helps reduce delays in information transfer that might result from routing sensor data through the central BMDS system. A way to communicate with interceptors in flight is also necessary to provide course corrections and other updates after the interceptors have been launched.

In the case of surface BPI sites, the communications equipment would need to be packaged so that it could be deployed to forward locations. For those sites, CBO assumed a support package similar to the one planned by the Missile Defense Agency, which includes a direct data downlink to the BPI site from orbiting BMDS sensors, a two-way data link to communicate with an interceptor during flight, and other links to integrate the site into the BMDS.[1] (Those components are described in more detail later in this chapter.) For a space-based BPI system, CBO assumed that the corresponding functions would be included as part of each interceptor satellite.

Designs for Interceptors

The considerations involved in selecting an interceptor design differ for surface-based systems and space-based systems. For example, surface-based interceptors must be able to survive the high mechanical and thermal stresses associated with flying through the atmosphere at supersonic speeds. Space-based interceptors, by contrast, will have little or no interaction with the atmosphere because intercepts will usually occur at very high altitudes. CBO used the analysis of performance needs outlined in Chapter 2 as a guide to develop various notional interceptor designs for comparison. The purpose was not to perform a detailed, engineering-level design analysis but to understand the impact of certain characteristics on the cost of interceptors and their suitability for use in the field.

Surface-Based Interceptors

From the standpoint of effectiveness, a primary trade-off in designing a surface-based interceptor is between speed and acceleration on the one hand and size on the other. High speed lengthens an interceptor's reach, improving its effectiveness against more-advanced ICBMs, increasing flexibility about where it is based, and potentially reducing the number of sites needed to counter a given threat. Small interceptor size allows a BPI system to be moved more easily to face emerging threats and, once in place, to be a less intrusive presence in a host country. Because the cost of boosters generally increases or decreases with size, smaller boosters can have cost advantages as well. In general, however, higher burnout velocities and shorter burn times—the two parameters that determine interceptor reach—require larger boosters with greater thrust.

A number of characteristics affect the details of the trade-off between interceptor speed and size. They include the propulsion efficiency of the booster, the mass of its structures, the number of booster stages, and the mass of the payload.

- The efficiency of the propulsion system is characterized by a single factor known as the specific impulse (I_{sp}). Measured in seconds, I_{sp} represents the thrust per unit of weight flow of propellant expelled by the rocket motor. Typical solid-fuel rocket motors have I_{sp} values of around 280 seconds. By comparison, the advanced liquid-fuel main engines on the Space Shuttle have an I_{sp} of about 450 seconds.

- A booster's structural mass, which includes all components other than the propellant and the payload, is an important design consideration because it represents additional weight that must be accelerated by the rocket. In general, as booster acceleration increases, additional structural mass is needed to handle increased mechanical stresses on the interceptor.

- Most large boosters use multiple stages to help reduce structural mass. Because each stage is jettisoned after its fuel is expended, subsequent stages have less structural mass to accelerate. Two stages are usually adequate for speeds of around 6 kilometers per second. Additional stages are usually preferred for higher speeds.

- Like structural mass, payload mass is an important determinant of interceptor size. For a surface-based BPI interceptor, the payload consists primarily of the kill vehicle and a shroud that gives the interceptor's nose

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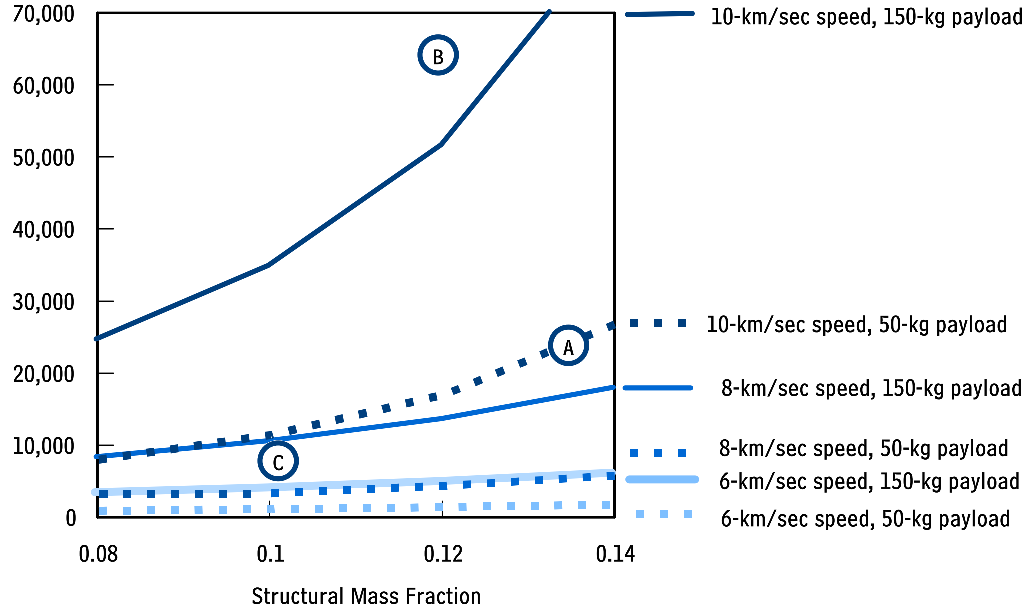
[1] Terry Little, "Kinetic Energy Interceptors Overview" (unclassified briefing by the Missile Defense Agency to Congressional Budget Office staff, November 13, 2003).

Figure 3-1.

Effect of Interceptor Speed and Payload Mass on the Mass of a Surface-Based Interceptor

(Kilograms)



Sources: Congressional Budget Office; Terry Little, "Kinetic Energy Interceptors Overiew" (unclassified briefing by the Missile Defense Agency to Congressional Budget Office staff, November 13, 2003); and Duncan Lennox, ed., *Jane's Strategic Weapons Systems*, vol. 39 (Coulsdon, Surrey: Jane's Information Group, July 2003), p. 388.

Notes: The figure assumes that the interceptors' boosters have a specific impulse of 280 seconds.

The structural mass fraction is the ratio of an interceptor's structural mass (the mass of everything other than the propellant and the payload) to the interceptor's total mass.

Point A shows the Missile Defense Agency's Ground-Based Midcourse Defense system interceptor (speed of 7-8 km/sec, peak acceleration of less than 9g); Point B shows the notional boost-phase interceptor from a 2003 study by the American Physical Society (speed of 10 km/sec, peak acceleration of about 60g); Point C shows the notional boost-phase interceptor from the Missile Defense Agency (speed of 6 km/sec, peak acceleration of about 20g).

km/sec = kilometers per second; kg = kilograms.

an aerodynamically efficient shape and protects the kill vehicle from atmospheric heating.

The impact that those characteristics have on interceptor speed and size is quantified by a relationship well known in the space-propulsion field: the rocket equation. That equation enables users to calculate how interceptor mass varies as a function of structural mass, payload mass, and interceptor speed and acceleration (booster burn time). Interceptor characteristics that provide the desired operational performance can be chosen from the relationships established in the rocket equation. The selection of burn time is a compromise between the desire for high acceleration (to increase interceptor reach) and the penalty of high acceleration (larger and heavier boosters to provide greater thrust and withstand greater thermal and mechanical stresses). Additionally, interceptors with shorter burn times typically require greater maneuverability on the part of the kill vehicle because the ability to make trajectory corrections with steering commands to the booster ends earlier in the interceptor's flight. Trajectory corrections after booster burnout must be made by the kill vehicle. Greater kill-vehicle maneuverability in turn results in greater weight.

In general, the need for higher acceleration increases as the time available for interceptor flyout decreases. CBO's alternative designs for surface-based interceptors—which

Table 3-1.

Characteristics of Various Current or Proposed Kill Vehicles

Vehicle	Phase Used	Mass (Kilograms)	Divert Velocity (Kilometers per second)	Sensors
EKV (Used by MDA's Ground-Based Midcourse Defense system)	Midcourse	68	Less than 1	Dual-band medium-wavelength infrared Charge-coupled device television
SM-3 (Used by Aegis ballistic missile defense system)	Ascent, Midcourse	20	Less than 1	Single-color long-wavelength infrared
Notional Design from the American Physical Society's Boost-Phase Intercept Study[a]	Boost	140	2.5	Infrared Visible Laser detection and ranging (lidar)
Notional Advanced-Technology Design from Lawrence Livermore National Laboratory	Boost	30	2.5	Short- and medium-wavelength infrared Ultraviolet/visible Laser detection and ranging (lidar)

Source: Congressional Budget Office.

Note: MDA = Missile Defense Agency.

a. *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues* (Washington, D.C.: American Physical Society, July 2003), available at www.aps.org/public_affairs/popa/reports/nmd03.cfm.

envision speeds of 6, 8, or 10 km/sec—are based on a 60-second burn time, which is suitable against the representative liquid- and solid-fuel threat ICBMs. The Missile Defense Agency's planned BPI booster is expected to have a similar total burn time for its two primary booster stages.[2] For CBO's 6-km/sec design, decreasing the burn time to 45 seconds would increase the interceptor's reach by about 35 km (less than 4 percent) at the cost of about 2,000 kilograms (kg) in additional weight (a 60 percent increase) and therefore greater expense. Although the acceleration forces resulting from a 60-second burn time are high—especially for the 10-km/sec design, which has acceleration of almost 40g—they are not unprecedented. For example, the Sprint missile that was part of the Safeguard antiballistic missile system in the 1970s used a five-second burn time that generated approximately 100g acceleration.

For a given interceptor speed, decreasing payload mass can provide substantial reductions in total interceptor size (see Figure 3-1 on page 23). For example, in the case of a 6-km/sec interceptor with a 0.1 structural mass fraction (the ratio of the interceptor's structural mass to its total mass), reducing the payload mass by a factor of three (from 150 kg to 50 kg) would reduce the interceptor weight by about a factor of three as well. (The I_{sp} of 280 seconds used in Figure 3-1 is consistent with efficient solid-fuel rockets preferred for military use.)

The main variable in payload mass is the mass of the kill vehicle. Existing and proposed kill vehicles vary widely in mass, from a few tens of kilograms to well over 100 kg (see Table 3-1).[3] Kill vehicle masses for BPI could range from as high as 140 kg, a figure estimated in a 2003 report by the American Physical Society (APS), to less than 30 kg for very small interceptors proposed by engineers at Lawrence Livermore National Laboratory.[4] For its options, CBO selected various kill-vehicle masses from that

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[2] "KEI Contractors Borrow from Other MDA Programs to Meet Schedule," *Inside the Pentagon*, April 15, 2004, p. 1.

[3] For more details about the components of kill vehicles, see Appendix B.

[4] See *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues* (Washington, D.C.: American Physical Society, July 2003), available at www.aps.org/public_affairs/popa/reports/nmd03.cfm. The Lawrence Livermore information was reported to the Congressional Budget Office in an unclassified briefing by Lawrence Livermore staff in November 2003.

Table 3-2.

Potential Trade-Offs in Designing Surface-Based Boost-Phase Interceptors

Structural Mass Fraction[a]	Payload Mass[b] (Kilograms)	Launch Mass (Kilograms)	Length (Meters)	Diameter (Meters)	Peak Acceleration (g)
		Interceptor Speed of 6 Kilometers per Second with Two-Stage Booster			
0.08[c]	**150**	**3,088**	**8.3**	**0.7**	**21.7**
0.08	300	6,176	10.4	0.9	21.7
0.10	150	3,735	8.8	0.7	21.7
0.10	300	7,470	11.1	0.9	21.7
		Interceptor Speed of 8 Kilometers per Second with Three-Stage Booster			
0.10[d]	**50**	**3,469**	**8.6**	**0.7**	**26.8**
0.10	150	10,408	12.4	1.0	26.8
0.12	50	4,487	9.4	0.8	26.8
0.12	150	13,462	13.5	1.1	26.8
		Interceptor Speed of 10 Kilometers per Second with Three-Stage Booster			
0.10	50	11,582	12.9	1.1	39.3
0.10	150	34,745	18.5	1.5	39.3
0.12[e]	**50**	**17,160**	**14.7**	**1.2**	**39.3**
0.12	150	51,480	21.1	1.8	39.3

Source: Congressional Budget Office.

a. The ratio of an interceptor's structural mass (the mass of everything other than the propellant and payload) to the interceptor's total mass.

b. Consists primarily of the mass of the kill vehicle and of the interceptor shroud.

c. CBO's Option 1.

d. CBO's Option 2.

e. CBO's Option 3.

range, recognizing that producing a 30-kg kill vehicle with BPI performance would require a technological leap in miniaturization. The midcourse-intercept kill vehicle on the BMD version of the Navy's Standard missile (SM-3) is lighter than that, but it has significantly less maneuverability (divert velocity) than a kill vehicle designed for boost-phase intercept.

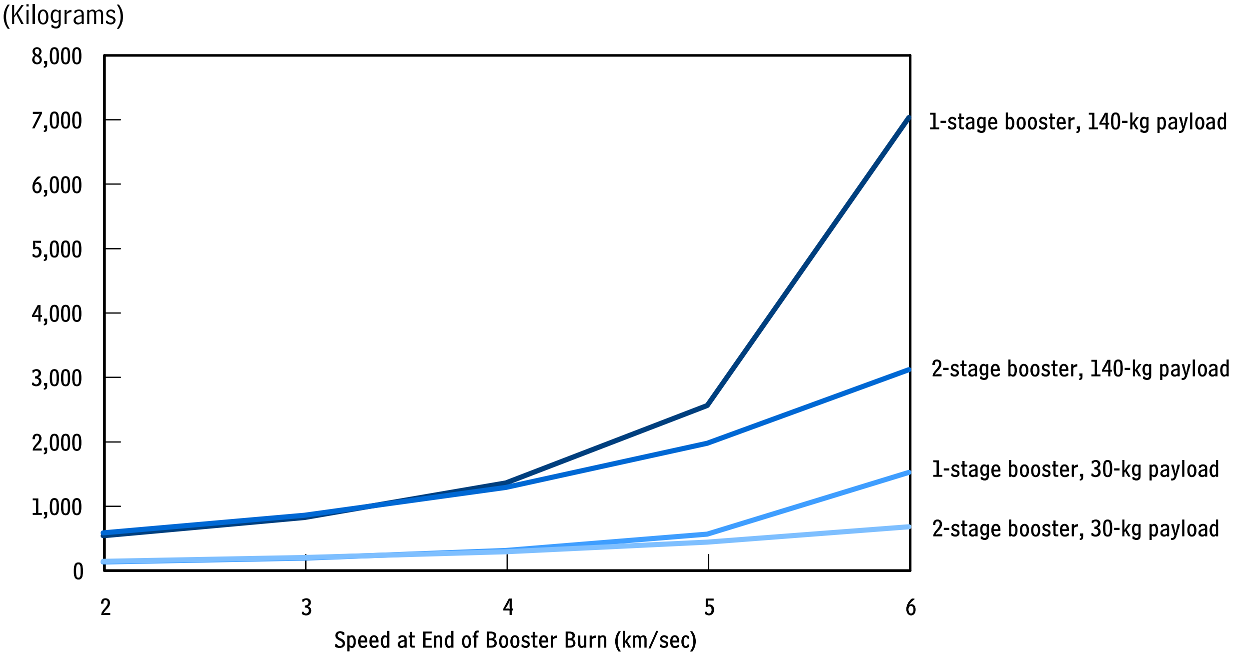
CBO chose its alternative designs for surface-based interceptors from a range of characteristics appropriate for the BPI mission (see Table 3-2). The designs span the range of interceptor speeds analyzed in Chapter 2 and a range of payload masses consistent with existing or proposed kill vehicles. The bold lines in Table 3-2 represent the interceptors chosen for CBO's three surface-based BPI options. The interceptor with the slowest speed, 6 km/sec, includes a two-stage booster. A three-stage booster design is more efficient for the higher-speed options (8 and 10 km/sec). For those higher speeds, the benefit that the extra stage provides by shedding structural mass earlier is worth the added complexity of the booster.

Space-Based Interceptors

As explained in Chapter 2, the number of interceptors in a space-based BPI constellation depends on the characteristics of the threat, the commit time, and the speed of the interceptors. From the perspective of interceptor design, for a given threat and commit time, a constellation can consist of either a smaller number of faster interceptors or a larger number of slower interceptors. However, the ad-

Figure 3-2.

Effect of Interceptor Speed and Payload Mass on the Mass of a Space-Based Interceptor



Source: Congressional Budget Office.

Notes: The figure assumes that the interceptors have an acceleration of 10g.

kg = kilograms; km/sec = kilometers per second.

vantage that faster SBIs offer in terms of needing fewer satellites can come at the price of greater mass per interceptor. As with surface-based systems, SBI mass varies with characteristics such as speed, acceleration, and payload mass. With the same payload mass, a single-stage 4-km/sec interceptor will be considerably lighter than a single-stage 6-km/sec interceptor. Even the added efficiency (and complexity) of a second stage cannot drop the mass of the 6-km/sec design down to that of the single-stage 4-km/sec design (see Figure 3-2).

The cost to launch a constellation into orbit may be the most important factor when choosing between interceptor speed and number of interceptors. Launch costs currently average about $20,000 per kilogram of mass delivered to low-Earth orbit. If the cost to launch an SBI was comparable to its procurement cost, the most cost-effective constellation could be one that required putting the least mass into orbit. As an example, for a constellation sized to defend against liquid-fuel ICBMs from North Korea and Iran, the lowest-mass design would be one with 4-km/sec interceptors, assuming a 30-kg kill vehicle, a commit time of 60 seconds, and interceptor acceleration of 10g (see Figure 3-3). Speeds below 4 km/sec would require both a larger number of SBIs and larger launch masses. Speeds above 4 km/sec would also require larger launch masses, despite a smaller number of SBIs needed.

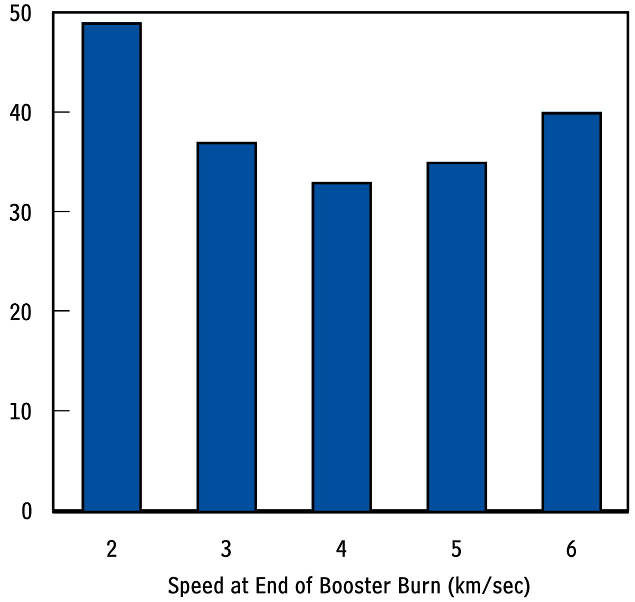
The masses shown in Figure 3-3 include only the interceptors themselves. Each SBI will also need an orbital support system, or "life jacket," consisting of shielding to protect the interceptor from its environment (if necessary), a propulsion system to control the satellite's attitude and maintain the proper position in orbit, and equipment to communicate with the necessary sensors, the interceptor in flight, and the BMDS. The mass of the life jacket can vary depending on the functions it is expected to carry out as well as specifics of the constellation's orbits. That mass is important because it can add considerably to the mass that must be put into orbit.

CBO considered two alternative life-jacket masses: 0.5 times the total mass of the SBI (a number based on the

Figure 3-3.

Total Mass of SBI Constellation Needed to Counter Liquid-Fuel ICBMs, by Interceptor Speed

(Thousands of kilograms)



Source: Congressional Budget Office.

Notes: The figure assumes that interceptors have an acceleration of 10g, that kill vehicles weigh 30 kilograms each, and that the system has a commit time of 60 seconds. It also assumes that the threat country does not launch more than one ICBM at a time and that only one interceptor is fired at an ICBM.

The total mass shown here reflects only the mass of the interceptors, not of the life jackets.

SBI = space-based interceptor; ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

APS study's analysis of what might be needed to support an SBI) and 0.2 times the total SBI mass (a number that reflects the possibility of a more advanced miniaturized design). Life-jacket mass can be expected to be roughly proportional to interceptor mass because two of its important functions—shielding and propulsion for maneuvering in orbit—are also proportional to interceptor size.

Other Design Considerations for a BPI System

Although sensors, battle management systems, and interceptors will determine the fundamental capability of a BPI system, other factors will contribute to its ultimate effectiveness once it has been deployed and to its cost. Those factors include the number of interceptors fired at a given target and the number of transport vehicles and ships needed for a surface-based system.

Number of Shots Taken at a Target

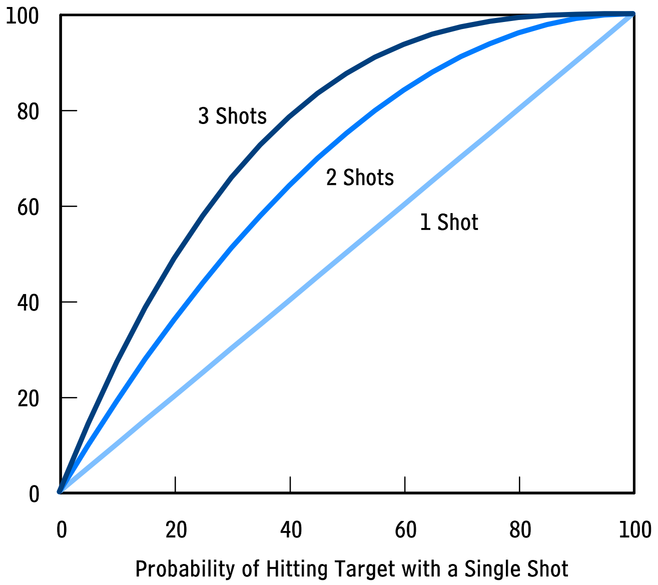
A surface-based BPI site could consist of as little as one interceptor and its associated command, control, battle management, and communications (C2BMC) equipment. Although such a site would offer a basic defensive capability, an actual operational site would most likely be structured to provide greater capability. At a minimum, an engagement against one ICBM would probably include two interceptor shots to increase the likelihood of a successful intercept.

The probability that an interceptor will hit its target depends on two other probabilities: that the interceptor will function as designed (its reliability) and that it will actually intercept the target (its accuracy). Because of the uncertainties involved in an ICBM's flight, even a perfectly functioning BPI system has some chance of simply missing its target. The overall probability of a successful intercept varies with the single-shot probability of a successful intercept and with the number of shots taken (see Figure 3-4).

Figure 3-4.

Probability of a Successful Intercept, by Number of Shots Taken

(Percent)



Source: Congressional Budget Office.

The probability of intercept that can be achieved with a single shot might not be considered adequate against such an important target as an ICBM headed for the United States. Consequently, additional BPI shots might be desired to increase the overall probability of a successful intercept. Because of the short engagement times for BPI, not enough time would be available to wait and see whether the first interceptor was unsuccessful before firing a second shot. Instead, the shots would have to be fired in a salvo as soon as a tracking solution was established. Such "shoot-shoot" tactics could also apply to a space-based system.

For its surface-based BPI options, CBO assumed that an individual site would include one set of C2BMC equipment and six interceptors. Each site would thus be capable of conducting a shoot-shoot engagement against three ICBMs. If the site's C2BMC equipment could handle six interceptors simultaneously, all three threats could be engaged at the same time. For the space-based options, CBO assumed enough interceptors to provide the opportunity for two shots against an ICBM.

Additional Equipment for Surface-Based BPI Systems

Estimates of the costs of CBO's options for surface-based BPI systems include the vehicles needed to transport interceptors and C2BMC equipment. Whenever possible, CBO used MDA's estimates of vehicle requirements. Because those requirements are specific to each option, they are presented separately as part of the option. (More details about that and other elements of the cost estimates can be found in Appendix A.)

The three options for surface-based BPI all assume that some interceptors could be based at sea on government-owned commercial cargo ships, if necessary. Cost estimates for those options include the purchase and operation of three cargo ships—enough to provide one or two sea-based BPI sites at any given time (with the other ships in transit or in maintenance). Alternatively, Navy surface combat ships might be modified to carry and launch boost-phase interceptors. However, because the interceptors envisioned in CBO's options are too large to fit into the vertical missile launchers found on today's surface combatants, considerable modifications would be necessary. MDA's plans include initial experimentation with operating surface-based BPI systems from a converted cargo ship, followed by a more substantial research and development effort (costing more than $2 billion through 2013) to integrate BPI launchers into either commercial or Navy ships.

Table 3-3.

Comparison of CBO's Options for a Surface-Based BPI System

	Option 1	Option 2	Option 3
Characteristics of Interceptors			
Length (Meters)	8.3	8.6	14.7
Diameter (Meters)	0.7	0.7	1.2
Launch Mass (Kilograms)	3,088	3,469	17,160
Kill-Vehicle Mass (Kilograms)	140	30	30
Structural Mass Fraction	0.08	0.10	0.12
Speed (Kilometers/second)	6	8	10
Burn Time (Seconds)	60	60	60
Peak Acceleration (g)	22	27	39
Procurement Quantities			
Mission Sets (Sites)	10	10	10
Ships for Sea Basing	3	3	3
Operational Interceptors[a]	60	60	60
Test and Spare Interceptors[b]	52	52	52

Source: Congressional Budget Office.

a. Six per site.

b. Assuming 40 tests over a 20-year period.

The BPI Options Examined in This Analysis

As explained above, CBO developed a range of illustrative BPI systems to investigate how much investment might be needed to provide different levels of BPI capability against ICBM threats to the United States (see Tables 3-3 and 3-4). The parameters of each option and the rationale behind it are described below, preparatory to the comparison of the options' capabilities and costs in the next chapter.

Option 1: 6-km/sec Surface-Based Interceptors

Option 1 represents the sort of system that might be developed if policymakers believed that deploying defenses as soon as possible was critical. The interceptors in this option provide sufficient performance to engage liquid-fuel ICBMs fired from all but the largest countries. They are also small enough to be transported by large military cargo aircraft.

This system uses a two-stage booster and a heavy (about 140-kg) kill vehicle. The booster performance and kill-vehicle size are within the current state of the art.

Each BPI site in Option 1 includes the required C2BMC equipment and vehicles as well as six interceptors, mounted in pairs on three mobile launchers. That configuration would enable each site to conduct a shoot-shoot engagement against three threat ICBMs without reloading its launchers. Overall, the option would involve setting up 10 operational sites (including the purchase of three cargo ships for sea basing). The implications for both cost and operational effectiveness of different procurement quantities are discussed in Chapter 4.

Option 2: 8-km/sec Surface-Based Interceptors

Option 2 is representative of a system that might be developed if defeating solid-fuel ICBMs was considered a priority or if reducing the number of sites needed to cover large threat countries was an important consideration. This system offers greater interceptor performance than the system in Option 1 but maintains comparable size and mobility.

Option 2 employs a three-stage booster and a lightweight (30-kg) kill vehicle. A light kill vehicle is necessary to keep the interceptors small enough for transport by aircraft. The 30-kg mass is similar to that of an advanced-technology kill-vehicle concept proposed by engineers at Lawrence Livermore. The structural mass fraction is higher than in Option 1 to account for the interceptor's higher acceleration.

Option 2 includes the same C2BMC equipment and launchers as Option 1, as well as 10 operational sites and three ships.

Option 3: 10-km/sec Surface-Based Interceptors

Option 3 illustrates a system designed specifically to counter solid-fuel ICBMs. That capability comes at the expense of mobility, because the interceptors' boosters and launchers would be large and heavy.

Option 3 uses 10-km/sec interceptors, the fastest considered in this analysis. It employs the same lightweight kill vehicle as Option 2 but requires a significantly larger and higher-performance booster to achieve that higher speed. As a result, Option 3's launch mass is nearly five times greater than that of Option 2. The structural mass fraction is also higher than in Option 2 to account for the interceptors' higher acceleration. With a speed of 10 km/sec, the interceptors in this option are similar in performance to the fastest interceptor considered in the APS study. However, they are smaller than that interceptor because they carry a lighter kill vehicle.

Table 3-4.

Comparison of CBO's Options for a Space-Based BPI System

	Option 4	Option 5
Characteristics of Interceptors		
Length (Meters)	5.4	4.3
Diameter (Meters)	0.4	0.4
Launch Mass (Kilograms)	847	442
Kill-Vehicle Mass (Kilograms)	140	30
Structural Mass Fraction	0.1	0.1
Life-Jacket Mass	0.5 times SBI mass	0.2 times SBI mass
Speed (Kilometers/second)	4	6
Burn Time (Seconds)	40	30
Average Acceleration (g)	10	20
Procurement Quantities		
Operational Interceptors for Constellation	368	156
Interceptors for Replenishment[a]	848	384
Test and Spare Interceptors[b]	37	16

Source: Congressional Budget Office.

Note: SBI = space-based interceptor.

a. Over a 20-year period.

b. No purchases for testing would be necessary because operational SBIs at the end of their service lives would be used for tests.

Option 3 includes the same C2BMC equipment and number of sites and cargo ships as the other surface-based BPI options. However, because of its large booster, each interceptor would require its own launcher.

Options 4 and 5: Two Constellations of Space-Based Interceptors

Option 4 and Option 5 are constellations of SBIs in low-Earth orbit. Like the three surface-based options, they encompass a range of interceptor performance. These two alternatives are described together because, unlike with the surface-based options, the variables of SBI performance and constellation size in these alternatives tend to trade off with one another to yield similar operational effectiveness for the system as a whole. The primary difference is one of cost.

The system in Option 4 consists of 4-km/sec SBIs with 140-kg kill vehicles (similar to the kill vehicles in Option 1). These interceptors have an average acceleration of 10g and a life-jacket mass equal to half the interceptor mass.

Option 5 uses a higher-performance SBI that takes advantage of potential advances in kill-vehicle weight reduction and general satellite miniaturization. The result is an interceptor with a 30-kg kill vehicle and a life-jacket mass only 0.2 times the interceptor mass. That high-end interceptor has a speed of 6 km/sec and an average acceleration of 20g.

The constellations envisioned in Options 4 and 5 are sized to defend against liquid-fuel ICBMs launched from locations between 25 degrees north latitude (southern Iran) and 45 degrees north latitude (northern North Korea) and to provide a shoot-shoot SBI engagement for increased probability of a successful intercept. That capability requires as few as 156 SBIs in the case of Option 5 and as many as 368 SBIs in the case of Option 4. The corresponding masses in orbit range from 83 metric tons (tonnes) for Option 5 to 468 tonnes for Option 4.

CHAPTER

4

Comparison of BPI Options

Although all of the alternative boost-phase intercept systems described in Chapter 3 are designed to provide full coverage against liquid-fuel intercontinental ballistic missiles launched from Iran and North Korea, they do not have identical capabilities. Each alternative has advantages and disadvantages inherent in its design. This chapter examines the most important distinctions between the alternatives in the areas of cost, coverage, capability against solid-fuel ICBMs, dependence on access to foreign bases, vulnerability to being attacked or to exhausting their supply of interceptors, and strategic responsiveness.

Not surprisingly, the greatest differences exist between the options for surface-based systems and space-based ones. Within each group, the alternatives with the slowest interceptors (Options 1 and 4) would present the smallest development challenges while still providing coverage against liquid-fuel ICBMs launched at the United States from countries like Iran and North Korea. Among the surface-based systems, the more-advanced designs in Options 2 and 3 would add the ability to defeat solid-fuel ICBMs launched from large countries (such as Iran) and the general ability to provide coverage with fewer BPI sites. However, the trade-off for those benefits would be greater technical risks in development and higher costs for development and deployment. With the space-based systems, by contrast, the more-advanced design in Option 5 would have lower costs than the less-advanced design in Option 4 (although, with the appropriate number of satellites, both options would offer similar effectiveness). The reason is that, with the cost assumptions underlying the space-based options, the additional development costs to reduce the weight and increase the speed of the interceptors in Option 5 would be more than offset by the lower production and launch costs that would result from fielding that option's smaller and lighter constellation.

Costs

The Congressional Budget Office estimated the costs of each BPI system in three areas: research and development (R&D), production, and operations. R&D includes the engineering activities needed to design and develop the booster, kill vehicle, and other components that make up the system. R&D costs also cover testing the hardware and integrating the BPI system into existing infrastructure and support elements. Production costs include those to manufacture surface-based interceptors and their associated support equipment or, in the case of a space-based system, to buy interceptors and launch services for the initial constellation. Operations costs cover routine efforts to maintain and operate the BPI system and to replenish its components over 20 years.

For each option, CBO calculated a basic, or low, estimate and a high estimate that accounts for potential cost growth comparable to what defense programs have experienced in the past. The range of costs that those two estimates represent also accounts for uncertainty about such factors as the maturity of a given technology and the complexity of manufacturing, both of which can affect costs (see Box 4-1). CBO used established cost-estimating relationships to calculate many production costs, such as for boosters and kill vehicles. Some of the estimates for R&D and operations costs, by contrast, were based on analogies with comparable systems, because of uncertainty in the engineering details of an option's design coupled with the unique characteristics of many components of a BPI system. More details about how CBO produced the cost estimates are available in Appendix A.

The costs of the illustrative BPI systems range from $16 billion to $37 billion (in 2004 dollars) for the surface-based systems in Options 1 through 3 and from $27 billion to $78 billion for the space-based systems in Options

Box 4-1.

The Role of Uncertainty in CBO's Estimates of the Costs of Boost-Phase Intercept Systems

In this analysis, the Congressional Budget Office (CBO) has not examined the entire range of possible configurations of systems for boost-phase missile defenses and how they might be developed and deployed. Decisions about what defensive systems to deploy and how to field them would depend on a number of factors, including the nature and extent of the threat that the United States would be likely to face in future years, the systems' potential effectiveness against such threats, and the possible reactions of U.S. allies and other nations to a decision to deploy a boost-phase missile defense system.

Besides questions about the structure and goals of a boost-phase missile defense system, other factors common to many Department of Defense (DoD) programs complicate the task of estimating costs. In particular, estimates for systems that are defined only conceptually or that depend on the development of new technologies entail more uncertainty than estimates for well-defined programs based on proven technologies.

To account for the possible effects of that uncertainty, CBO has provided a range of cost estimates for the boost-phase intercept (BPI) systems discussed in this study. For each alternative, the low estimate represents what the system might cost if few technical or schedule difficulties arose in making the system fully operational. The high estimate accounts for potential technical, schedule, and cost growth common for similar types of systems.

As explained in more detail in Appendix A, most of the factors that CBO used to estimate cost growth were developed by the RAND Corporation and based on unpublished updates of a 1996 report, *The Defense System Cost Performance Database: Cost Growth Analysis Using Selected Acquisition Reports*. CBO applied the results of that analysis to comparable systems that would be developed, built, and deployed as part of the BPI systems described in this study. For example, CBO developed the high estimate for BPI boosters by using cost-growth factors for the Minuteman and Trident strategic missiles. In addition to the factors developed by RAND, CBO developed its own cost-growth factors for launch vehicles and for system operating costs on the basis of the actual costs of comparable systems, such as the Atlas and Delta launch vehicles, the Patriot missile system, and the satellite-based Global Positioning System.

4 and 5 (see Table 4-1). One significant reason that the space-based systems would be more expensive, on the whole, is that those options envision deploying a greater number of interceptors than in the surface-based systems and include costs for launching those interceptors into orbit. Each of the surface-based options would buy 112 interceptors and deploy 60 of them to operational units (with the remaining 52 used for tests and as spares in case any of the operational interceptors malfunctioned or were damaged). Option 5, by comparison, would deploy 156 interceptors, and Option 4 would deploy 368.

Another factor that makes the space-based systems more expensive is the cost of sustaining the constellation of space-based interceptors. CBO assumed that orbiting SBIs would last for seven years (a life span typical of satellites in low-Earth orbit). In contrast, it assumed that surface-based interceptors could be designed to function for 20 years (a typical service life for that class of missile). Thus, over a 20-year period, each space-based system would need to be replaced about twice. Launch costs for the more-numerous and heavier Option 4 SBIs are a key reason that the lower-speed system in Option 4 would cost more than the higher-speed system in Option 5.

The costs of Options 4 and 5 are for a constellation to defend against liquid-fuel ICBMs from Iran and North Korea using a shoot-shoot engagement doctrine. Those costs might be lower if a single-shot doctrine was adopted instead, although that change could significantly decrease the constellation's effectiveness. However, because the BPI defensive layer is intended to complement a mid-

Table 4-1.

Summary of Costs for Boost-Phase Intercept Systems

(Billions of 2004 dollars)

	Surface-Based Systems						Space-Based Systems			
	Option 1		Option 2		Option 3		Option 4		Option 5	
Cost Category	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Research and Development	6.7	9.5	8.8	13.1	13.4	19.5	7.1	9.8	8.5	12.9
Initial Production										
Interceptors[a]	2.8	3.6	3.1	4.0	4.8	6.4	8.7	10.7	3.7	4.6
Surface equipment	0.6	0.7	0.6	0.7	0.8	1.0	n.a.	n.a.	n.a.	n.a.
Space launch	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	7.3	11.0	1.5	2.3
Subtotal	3.4	4.3	3.7	4.7	5.6	7.4	16.0	21.7	5.2	6.9
Operations Over 20 Years										
Routine operations and support	4.0	6.5	4.0	6.5	4.0	6.5	2.0	4.0	2.0	4.0
Operational test support	1.6	3.2	1.6	3.2	1.6	3.2	1.6	3.2	1.6	3.2
Replacement SBIs	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	16.1	19.9	7.2	9.0
Replacement SBI launches	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	12.8	19.2	2.6	3.9
Subtotal	5.6	9.7	5.6	9.7	5.6	9.7	32.5	46.3	13.4	20.1
Total	**15.7**	**23.6**	**18.1**	**27.5**	**24.6**	**36.6**	**55.6**	**77.8**	**27.1**	**39.9**

Source: Congressional Budget Office.

Notes: For details about the major characteristics and procurement quantities of each option, see Tables 3-3 and 3-4.

n.a. = not applicable; SBI = space-based interceptor.

[a] Includes interceptors used for testing, in the case of surface-based systems. (With space-based systems, tests would be performed using operational interceptors that had reached the end of their service lives.)

course defensive layer and perhaps eventually a terminal defensive layer, it may be acceptable to have a lower BPI effectiveness than would be the case if the BPI layer stood alone. The range of costs for a single-shot capability against liquid-fuel ICBMs would drop to $36 billion to $51 billion for Option 4 and to $20 billion to $31 billion for Option 5.

The surface-based systems in the first three options might be scaled back in a similar fashion. Against the representative threat of liquid-fuel ICBMs launched from Iran and North Korea, the 10 mission sets that each option would purchase would provide for five extra BPI sites in the case of Option 1 and seven extra sites in the case of Option 2 or Option 3. Those additional sites could be used to cover other threat countries or to provide more-robust coverage of both Iran and North Korea. Alternatively, cutting procurement quantities to five mission sets would, in principle, still allow for enough surface BPI sites to provide coverage of both Iran and North Korea. Costs for those scaled-back options might be as low as $14 billion to $21 billion for Option 1, $16 billion to $26 billion for Option 2, and $22 billion to $35 billion for Option 3.

Areas of the World Covered

Although the space-based options would cost considerably more than the surface-based options, they would also provide much greater coverage. Options 1 through 3 would cover only the countries against which the BPI systems were deployed (Iran and North Korea, for example, a total area of about 1.8 million square km), whereas Options 4 and 5 would cover the entire surface of the Earth between 25 and 45 degrees of both north and south latitude (a total area of about 145 million square km). However, because much of the latter area is ocean or countries that are not likely to pose a threat, it is difficult to quantify the value of the additional coverage. Proponents of space-based interceptors argue that the identity of future threats is uncertain and that coverage of the ocean is a valuable hedge against ICBMs launched from ships or submarines. In principle, a space-based system is also capable of covering very large countries—such as China or Russia—that are too big to be covered by surface interceptors located around their borders. However, the constellations in Options 4 and 5 would not cover high enough latitudes to defend against missiles launched from those countries.

Capability and Costs to Counter Solid-Fuel ICBMs

Each of the options analyzed in this report offers sufficient capability—in terms of the performance of the BPI system and the quantity of equipment purchased—to counter liquid-fuel ICBMs launched at the United States from anywhere in North Korea or Iran. As explained in Chapter 2, the effectiveness of BPI systems would need to be greater if, as some analysts argue might happen, threat countries were able to develop or acquire solid-fuel ICBMs (which have a shorter burn time). A system that would still be effective in that case might be a valuable hedge against uncertainties in the evolution of the ICBM threat.

To counter missiles with shorter burn times, a BPI system would need some combination of better performance (shorter commit times, faster interceptors) and more sites (to get defensive launchers closer to potential launch sites of ICBMs). Better performance can be difficult to achieve, however, in a system that has already been fielded. And in the case of surface-based BPI, locations for additional sites may not be available. (The availability of basing is discussed in the next section.)

The increased difficulty of countering solid-fuel ICBMs has different implications for each of CBO's options (see Table 4-2). Against a representative solid-fuel ICBM, Option 1 would only provide full coverage of smaller countries and only then if favorable basing locations were available and if commit times were short. For example, Option 1 could cover relatively small North Korea only if commit times could be held to less than 45 seconds or if several sites could be located in China. Although Option 1 would allow for enough sites to surround Iran, its 6-km/sec interceptors would lack the reach to cover launch locations deep in Iran's interior, assuming reasonable commit times.

Table 4-2.

Effects on CBO's Options of Targeting Solid-Fuel ICBMs

Option	Operational Impact	Cost Impact
1	Interceptors lack the reach to fully cover large countries	Not applicable
2	Seven launch sites needed to cover Iran versus five in the case of liquid-fuel ICBMs, leaving fewer sites available for other scenarios (if no additional interceptors are bought)	No additional purchases needed beyond the equipment for 10 launch sites assumed in the option
3	Four launch sites needed to cover Iran versus two in the case of liquid-fuel ICBMs, leaving fewer sites available for other scenarios (if no additional interceptors are bought)	No additional purchases needed beyond the equipment for 10 launch sites assumed in the option
4	Constellation of SBIs increases from 368 to 1,308	Additional $107 billion to $146 billion needed to buy more SBIs
5	Constellation of SBIs increases from 156 to 516	Additional $30 billion to $40 billion needed to buy more SBIs

Source: Congressional Budget Office.

Note: ICBM = intercontinental ballistic missile; SBI = space-based interceptor.

The greater performance inherent in Options 2 and 3 would give them greater capability against ICBMs with shorter burn times. Either alternative, using a site in the Sea of Japan, could counter a solid-fuel ICBM with a three-minute burn time launched from North Korea even if commit times exceeded 60 seconds. For full coverage of Iran, the number of sites needed under Option 3 would increase from two to four (for a 60-second commit time), and the number of sites needed under Option 2 would rise from two to seven. Those additional sites would not require buying more than the 10 mission sets included in each option, but they would leave fewer sites available to cover other areas (in addition to North Korea)—two in Option 2 and five in Option 3.

CBO's space-based options could also provide coverage against solid-fuel ICBMs, although a denser constellation of interceptors would be needed. With the 4-km/sec, 10g SBIs in Option 4, the necessary constellation size would grow to 1,308 satellites—more than triple the 368 needed to counter liquid-fuel ICBMs. In the case of Option 5, with 6-km/sec, 20g interceptors, the constellation size would increase to a similar extent, from 156 to 516 SBIs. For those larger constellations, total costs would more than double—to ranges of about $163 billion to $224 billion for Option 4 and $57 billion to $80 billion for Option 5.

Reliance on Access to Foreign Basing

Surface-based BPI systems would need to be deployed to sites in countries adjacent to the threat country being covered, which would require permission from the host nations. Lack of access to those areas could greatly affect operations. For example, in the recent conflict in Afghanistan, lack of transit rights over Iran forced aircraft operating from Kuwait to fly much longer distances down the Persian Gulf and up through Pakistan to reach targets in Afghanistan. In the case of missile defense, being denied basing access could complicate BPI efforts to the point of rendering them infeasible.

In general, a surface-based system that requires fewer sites will be less vulnerable to constraints on access than a system that needs more sites. Consequently, of the surface-based systems, the one in Option 3 would be the least vulnerable to access constraints, followed by the one in Option 2. Option 1 would be the most vulnerable. That order matches the relative speeds of the systems, which has a bearing on how many sites they need. A higher-speed surface system will never need more sites than a lower-speed system, but the specific number will depend on the scenario in question.

To defend against North Korean liquid-fuel ICBMs, all three options would need only one site in international waters (see Figure 4-1). Consequently, none would be vulnerable to denial of basing rights. To defend against liquid-fuel ICBMs from Iran, Option 1 would require four sites (roughly one on each side of the country), compared with two sites for Options 2 and 3. The additional vulnerability of Option 1 could be much more significant than a simple factor of two extra sites, however. The 8-km/sec and 10-km/sec interceptors in Options 2 and 3, respectively, would provide coverage from sites in Afghanistan and Iraq, where basing access might be available (at least when this report was being written). The additional sites needed for the 6-km/sec interceptors in Option 1 would be located in countries such as Turkmenistan, where access is less assured. (Of course, not long ago, access to sites in Afghanistan and Iraq would have been considered unattainable as well. In fact, Iraq was considered a potential threat country instead of a possible BPI site location.)

The ability to position surface-based systems where necessary will always be subject to geopolitical conditions. Space-based systems have the advantage of independence from such access constraints.

Vulnerability of the BPI System to Attack

Besides limitations on their location, another way in which BPI systems could be prevented from fulfilling their mission is if they were attacked by the threat country they were covering. Because surface-based BPI systems would be positioned close to the threat country, such an attack could be made before the country launched an ICBM.

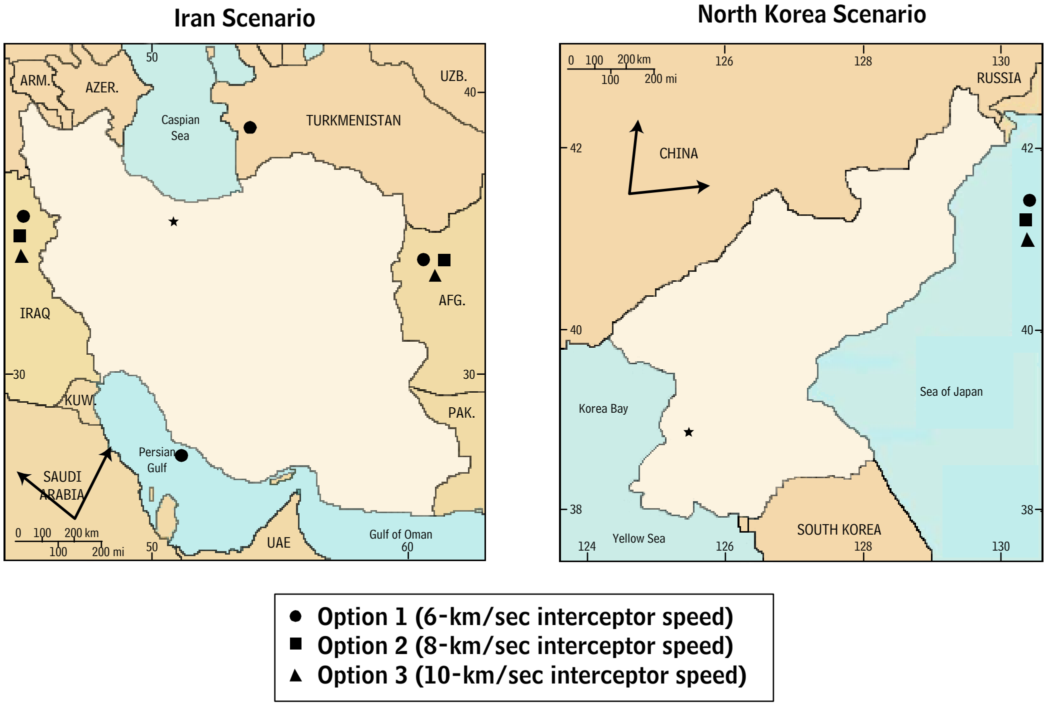
For the purposes of this analysis, all surface sites were assumed to be located approximately 100 km from the border of the threat country so they would be out of range of artillery or unguided rockets. However, short-range ballistic missiles or cruise missiles, as well as attack aircraft, from that country could reach a BPI surface site. Consequently, the site might require its own defenses, such as Patriot missiles for air defense and a ground force for perimeter defense. The costs of those defenses are not included in CBO's cost estimates. For their part, the space-based options would be potentially vulnerable to antisatellite weapons, should threat countries develop them.

Ability to Counter Increasing Numbers of ICBMs

The surface-based options envision deploying six interceptors at each site. With shoot-shoot tactics to improve the probability of destroying a target ICBM, each site would thus be capable of three BPI engagements. However, the threat country could try to saturate a defensive

Figure 4-1.

Location of Surface-Based BPI Sites Needed to Defend Against Liquid-Fuel ICBMs in CBO's Options



Iran Scenario

North Korea Scenario

Source: Congressional Budget Office.

Notes: The arrows on each map indicate the spread of trajectories at which ICBMs could be launched against the United States.

BPI = boost-phase intercept; ICBM = intercontinental ballistic missile; km/sec = kilometers per second.

site by launching more than three ICBMs or some combination of actual ICBMs and decoys intended to draw BPI fire. For example, it might launch several single-stage rockets on ICBM-like initial trajectories to force the defense—which must commit interceptors early to meet BPI timelines—to exhaust its supply of interceptors before an actual ICBM was launched. To counter that possibility, BPI sites could require additional interceptors and their associated launchers.

The number of interceptors needed to defend against additional ICBMs increases in proportion to the number of sites needed in a scenario. Consequently, the number would grow faster in the case of defenses against solid-fuel ICBMs because more sites are necessary to provide full coverage against those missiles.

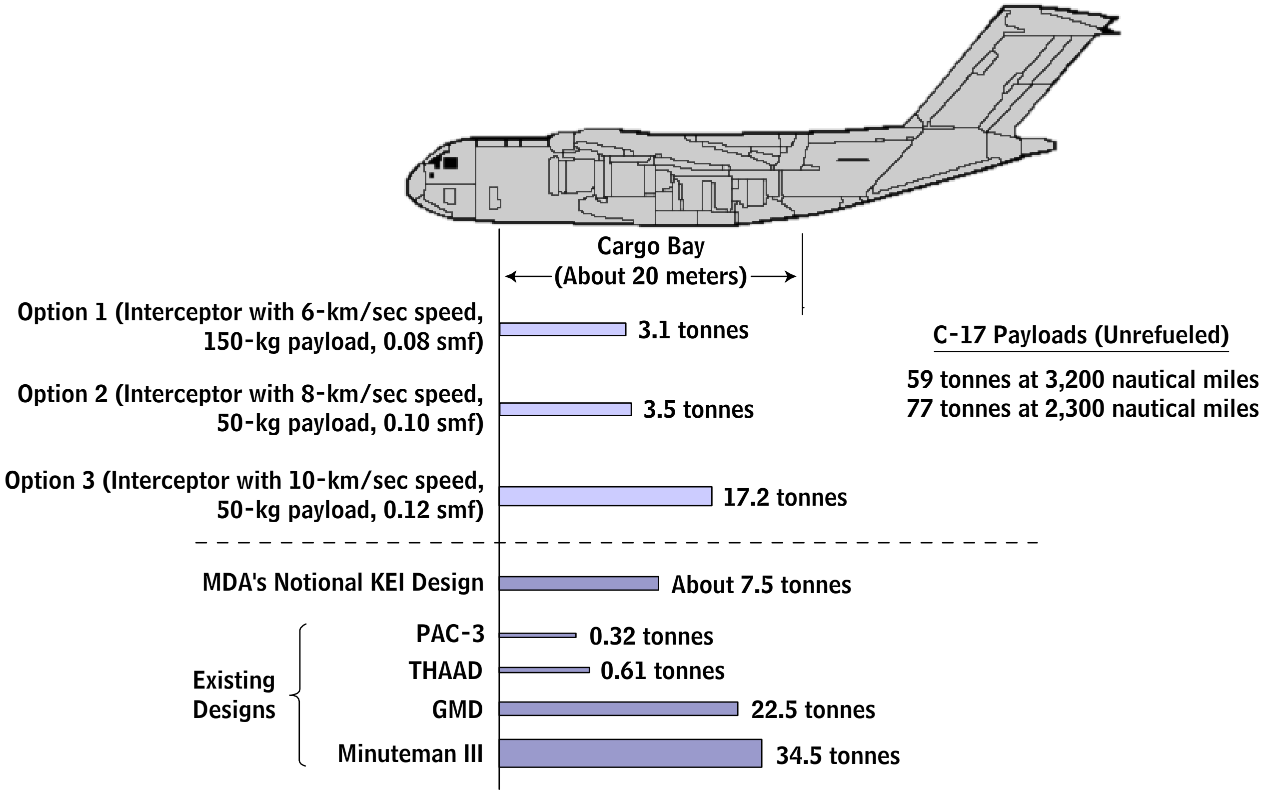
For space-based systems, the number of interceptors needed to counter multiple simultaneous ICBM launches would increase rapidly because the entire constellation would have to be "deepened," so that more interceptors were available at any given time. If the threat ICBMs were not launched simultaneously, however, the orbital motion of the satellites would bring new SBIs into position to fire at them in roughly 10 minutes.

Strategic Responsiveness

In terms of reacting quickly to newly emerging threats, Options 4 and 5, the space-based alternatives, would be the most strategically responsive if a threat arose between 25 and 45 degrees of latitude. The reason is that, once deployed in orbit, space-based interceptors would always be on alert. Surface-based systems, by contrast, would require time for deployment (as well as access) to areas on the perimeter of the threat country. Consequently, Options 4 and 5 are better suited to defeat a "bolt from the blue" type of attack from within the covered latitude bands.

Figure 4-2.

Size of Surface-Based BPI Interceptors Relative to the Cargo Bay of a C-17 Aircraft



Sources: Congressional Budget Office; Duncan Lennox, ed., *Jane's Strategic Weapons Systems*, vol. 39 (Coulsdon, Surrey: Jane's Information Group, July 2003); and Terry Little, "Kinetic Energy Interceptors Overiew" (unclassified briefing by the Missile Defense Agency to Congressional Budget Office staff, November 13, 2003).

Notes: The sizes and weights shown are for an interceptor (or missile) only. The interceptor payload masses include the mass of the kill vehicle and the shroud.

BPI = boost-phase intercept; km/sec = kilometers per second; kg = kilograms; smf = structural mass fraction; tonne = metric ton (1,000 kg); MDA = Missile Defense Agency; KEI = kinetic-energy interceptor; PAC-3 = Patriot Advanced Capability-3; THAAD = Terminal High Altitude Air Defense; GMD = Ground-Based Midcourse Defense.

If a threat arose at a latitude outside the band for which an SBI constellation was designed, surface-based systems would be better able to respond, because expanding the SBI constellation would be time- and satellite-intensive. Substantially changing the constellation's orbital inclination would not be possible with the fuel available to SBIs in orbit.

Of the surface-based systems, those in Options 1 and 2 would be more responsive than the system in Option 3 because their smaller size would allow for easier deployment by air. The differences in weight and size between the three types of surface-based interceptors in CBO's options are significant compared with the capacity of a C-17 aircraft, the Air Force's main strategic airlifter (see Figure 4-2). Even with a very light kill vehicle, a 10-km/sec interceptor would weigh nearly five times more than an 8-km/sec interceptor—over 17 metric tons (17,000 kilograms, or nearly 20 English tons). Although 17 metric tons is well below the payload limits of the C-17, the number of aircraft needed to deploy all of the equipment for a BPI site would still be higher under Option 3 than under Options 1 and 2 because each interceptor would require its own transport vehicle, only one of which would fit on an aircraft at a time. The smaller interceptors of the other surface-based options could be mounted in pairs on a similar transport vehicle, enabling an additional interceptor to be delivered in each aircraft.

The issue of air mobility aside, interceptors the size of those in Option 3 would be best suited to basing in fixed silos. That is the case for the Ground-Based Midcourse Defense system that the Department of Defense plans to field by the end of 2004 (initially at Fort Greely in Alaska and Vandenberg Air Force Base in California). Although such silos are practical on home territory, permanent BPI installations in foreign countries would be likely to pose greater access problems than mobile BPI systems.

The responsiveness of surface-based BPI systems could be worse if they used sea bases because of the transit time needed to get a ship carrying the system to the correct location. Basing BPI ships overseas, much as the Army and Marine Corps preposition equipment overseas, could improve the responsiveness of sea-based systems. Alternatively, equipment for a ground-based BPI site could be flown to a theater and temporarily placed on a local ship to provide interim coverage until the dedicated BPI ship arrived.

APPENDIX

A

CBO's Estimates of the Costs of Alternative BPI Systems

The Congressional Budget Office (CBO) developed five options for boost-phase intercept (BPI) systems to compare the systems' potential effectiveness and costs. As a basic requirement, each option's BPI system had to be capable of defending the United States against liquid-fuel intercontinental ballistic missiles (ICBMs) launched from Iran or North Korea; each alternative, however, featured a different interceptor to accomplish that mission. Three of the options were assumed to deploy surface-based interceptors; the other two options were assumed to use space-based interceptors. In developing each alternative, CBO assessed the technical characteristics of the chosen interceptor, the elements that the BPI system might comprise, and how those elements would work together to intercept and destroy an enemy missile. The analysis was based on a number of sources, including—when they were available—existing programs' technical requirements, schedules, and costs.

CBO has not examined all possible configurations of systems for boost-phase missile defense and how those configurations might be developed and deployed. Decisions about which defenses to deploy and how to deploy them would depend on a number of factors, including the nature and extent of the threats that the United States was likely to face in future years, the potential effectiveness of any missile defense system against such threats, and the possible reactions of allies and other nations to a decision to deploy a BPI system.

A Summary of the Options and Their Costs

CBO estimated how much it would cost, in 2004 dollars, to acquire the components for the five options considered in this study and to operate the resulting systems for 20 years. (See Chapter 3 for more-detailed noncost information about those components.) Total costs ranged from $16 billion to $37 billion for the surface-based systems and from $27 billion to $78 billion for the space-based alternatives.

Not explicitly included in CBO's comparison of the alternatives are the costs for the sensor architecture used to identify and track targets. The different systems are assumed to all use the same sensor architecture, which is based on the one that the Department of Defense (DoD) is planning to deploy to support missile defense requirements and for other purposes. For BPI, the important sensors are the space-based infrared satellites (SBIRS-High) now being developed by the Air Force. In creating its options, CBO assumed that those satellites or a comparable system would be fielded in time to support the BPI systems.

Estimates of costs for systems that are defined only conceptually or that depend on the development of new technologies entail more uncertainty than do estimates for well-defined programs based on proven technologies. To account for the potential effects of such uncertainty, CBO estimated a range of costs for the BPI systems it evaluated. For each alternative, the low estimate represents what the systems might cost if few technical difficulties arose in making them fully operational. The high estimate takes into account the growth in costs that has been common among such systems.

Option 1: Surface-Based Interceptors with a Speed of 6 Kilometers per Second

Option 1 represents the kind of BPI system that might be developed if the Administration determined that it was critical to deploy boost-phase missile defenses as soon as

Table A-1.

Estimated Costs of Surface-Based BPI Systems

(Billions of 2004 dollars)

	Option 1 (6-km/sec interceptors)		Option 2 (8-km/sec interceptors)		Option 3 (10-km/sec interceptors)	
Cost Category	**Low**	**High**	**Low**	**High**	**Low**	**High**
Research and Development[a]						
Boosters	2.2	3.1	2.5	3.5	5.3	7.4
Kill vehicles	0.5	0.8	1.7	2.9	1.7	2.9
Other components	1.2	1.6	1.2	1.6	1.2	1.6
Test and evaluation	0.9	1.3	0.9	1.3	1.4	2.0
System integration	1.9	2.7	2.5	3.7	3.8	5.6
Subtotal	6.7	9.5	8.8	13.1	13.4	19.5
Production[a]						
Interceptors	2.8	3.6	3.1	4.0	4.8	6.4
Mobile launchers	0.3	0.4	0.3	0.4	0.5	0.7
Cargo ships	0.2	0.2	0.2	0.2	0.2	0.2
Battle management and communication sets	0.1	0.1	0.1	0.1	0.1	0.1
Subtotal	3.4	4.4	3.7	4.7	5.6	7.4
Operations (Over 20 years)[b]						
Routine operations	1.8	2.7	1.8	2.7	1.8	2.7
Ship operations	1.2	1.8	1.2	1.8	1.2	1.8
Operational tests[c]	1.6	3.2	1.6	3.2	1.6	3.2
Operational integration	1.0	2.0	1.0	2.0	1.0	2.0
Subtotal	5.6	9.7	5.6	9.7	5.6	9.7
Total	**15.7**	**23.6**	**18.1**	**27.5**	**24.6**	**36.6**

Source: Congressional Budget Office.

Note: BPI = boost-phase intercept; km/sec = kilometers per second.

a. To produce the high estimates, CBO applied cost-growth factors to the low estimates. Those factors (48 percent for boosters and other components, 69 percent for kill vehicles, and 31 percent for communications equipment) were developed by the RAND Corporation on the basis of unpublished updates to a 1996 RAND report, *The Defense System Cost Performance Database: Cost Growth Analysis Using Selected Acquisition Reports*.

b. To produce the high estimates, CBO applied cost-growth factors it had developed (either 50 percent or 100 percent, depending on the relative level of cost uncertainty) to the low estimates.

c. The components for testing are purchased during the production phase.

possible. CBO estimated that acquiring the components of such a system and operating it for 20 years would cost between $16 billion and $24 billion (see Table A-1).

The interceptor used in this option could engage liquid-fuel ICBMs fired from all but the largest threat countries and would be small enough to be easily deployed by aircraft. The interceptor would have a two-stage booster and a kill vehicle of 140 kilograms (kg).

For all three surface-based options, CBO assumed that DoD would deploy 60 interceptors in 10 mobile batteries (or launch sites) by 2012 and would purchase and operate three cargo ships for basing batteries at sea.[1] Each site would comprise six interceptors mounted in pairs on three mobile launchers and one set of command, control, battle management, and communications (C2BMC) equipment—a configuration that would enable each site to engage three targets, shooting at each one twice without reloading its launchers. An additional assumption incorporated in the surface-based options was that the Missile Defense Agency (MDA) would purchase 52 more interceptors: 40 for operational testing and 12 for use as spares.

Option 2: Surface-Based Interceptors with a Speed of 8 Kilometers per Second

Option 2 reflects the kind of system that might be developed if DoD's highest priority was to defeat solid-fuel ICBMs or to reduce the number of sites required to cover large countries. Acquiring the necessary components of this system and operating them for 20 years would cost between $18 billion and $28 billion, CBO estimates.

Option 2's interceptor would be faster than Option 1's but still comparably mobile, with a three-stage booster and a lightweight (30-kg) kill vehicle. (That size kill vehicle is similar to a concept developed by the Lawrence Livermore National Laboratory.) Moreover, this option's interceptor would have a larger structural mass fraction than Option 1's interceptor so as to survive the stresses associated with its greater acceleration.[2] However, the structure of Option 2's BPI system would be identical to that of Option 1's: 10 launch sites, each containing six interceptors mounted in pairs on three mobile launchers and one set of C2BMC equipment.

Option 3: Surface-Based Interceptors with a Speed of 10 Kilometers per Second

The BPI system in Option 3 was designed specifically to counter solid-fuel ICBMs. CBO estimated that acquiring components for such a system and operating them for 20 years would cost between $25 billion and $37 billion.

The greater ability to engage solid-fuel ICBMs would come at the expense of mobility, because in this option, the interceptor's booster and mobile launcher would be larger and heavier than those in the other surface-based options. CBO assumed that the interceptor would use the same lightweight kill vehicle used in Option 2 but would require a significantly larger and higher-performance booster to achieve its faster speed. Indeed, the total interceptor mass (launch mass) of the interceptor in this option would be nearly five times that of Option 2's interceptor. Moreover, this interceptor would have a greater structural mass fraction than any of the other alternatives' interceptors because it would accelerate even faster than the interceptor in Option 2.

Option 3 includes the same number of launch sites, C2BMC equipment, and cargo ships as the other surface options do. Because of its larger booster, however, each interceptor in Option 3 would require its own mobile launcher.

Option 4: Space-Based Interceptors with a Speed of 4 Kilometers per Second

Under Option 4, a constellation of space-based interceptors (SBIs) would be deployed in low-Earth orbit, each interceptor having a speed of 4 kilometers per second and a 140-kg kill vehicle similar to that described for Option 1. The interceptor envisioned for this option would have an average acceleration of 10g (10 times the Earth's gravitational pull); its life jacket (which provides support functions such as propulsion for maneuvering in orbit) would have half the mass of the interceptor as a whole. CBO estimated that the costs to acquire the components included under this option, launch them into orbit, and operate them for 20 years would total between $56 billion and $78 billion (see Table A-2).

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[1] An inventory of three ships would allow for deployment of one or two sea-based sites at a given time (with the additional ships in transit or in maintenance).

[2] The structural mass fraction is the ratio of an interceptor's structural mass (that of all components other than the propellant and the payload) to its total mass.

Table A-2.

Estimated Costs of Space-Based BPI Systems

(Billions of 2004 dollars)

	Option 4 (4-km/sec interceptors)		Option 5 (6-km/sec interceptors)	
Cost Category	**Low**	**High**	**Low**	**High**
Research and Development[a]				
Boosters	2.7	3.8	2.0	2.9
Kill vehicles	0.5	0.8	1.7	2.9
Other components	1.0	1.3	1.6	2.4
Test and evaluation	0.9	1.1	0.8	1.0
System integration	2.0	2.8	2.4	3.7
Subtotal	7.1	9.8	8.5	12.9
Production[a]				
Interceptors	8.7	10.7	3.7	4.6
Launch services	7.3	11.0	1.5	2.3
Subtotal	16.0	21.7	5.2	6.9
Operations (Over 20 years)[b]				
Routine operations	1.0	2.0	1.0	2.0
Operational tests	1.6	3.2	1.6	3.2
Operational integration	1.0	2.0	1.0	2.0
Replacement interceptors	16.1	19.9	7.2	9.0
Launch services	12.8	19.2	2.6	3.9
Subtotal	32.5	46.3	13.4	20.1
Total	**55.6**	**77.8**	**27.1**	**39.9**

Source: Congressional Budget Office.

Note: BPI = boost-phase intercept; km/sec = kilometers per second.

a. To produce the high estimates, CBO applied cost-growth factors to the low estimates. Those factors (48 percent for boosters, 69 percent for kill vehicles and other components, and 31 percent for communication equipment) were developed by the RAND Corporation on the basis of unpublished updates to a 1996 RAND report, *The Defense System Cost Performance Database: Cost Growth Analysis Using Selected Acquisition Reports*.

b. To produce the high estimates, CBO applied cost-growth factors it had developed to the low estimates. It used a factor of 100 percent for routine operations, operational tests, and operational integration. The factors it used to increase the costs of replacement interceptors were the same as those used to increase production costs. The factor used to increase launch-vehicle costs was 50 percent (based on the actual costs of comparable systems).

The constellation of SBIs that this option would deploy is sized to defend the United States against liquid-fuel ICBMs launched from locations between 25 degrees north latitude (southern Iran) and 45 degrees north latitude (northern North Korea).[3] It would provide a shoot-shoot engagement by the SBIs (two interceptors would engage each target) to increase the probability of a successful intercept. Achieving that capability would require making 28 launches with heavy-lift launch vehicles to place 368 SBIs in orbit.

Option 5: Space-Based Interceptors with a Speed of 6 Kilometers per Second

Like Option 4, Option 5 would consist of a constellation of space-based interceptors in low-Earth orbit. However, those interceptors would be lighter and faster than the SBIs deployed under Option 4. Acquiring and deploying the necessary components and operating them for 20 years would cost between $27 billion and $40 billion, CBO estimates.

The interceptors to be deployed under Option 5 would have a speed of 6 kilometers per second and a 30-kg kill vehicle similar to the ones used in Options 2 and 3. This option's interceptors would have an average acceleration of 20g and a life jacket with one-fifth the mass of the interceptor as a whole. Like the SBI constellation in Option 4, this option's constellation would be sized to defend against liquid-fuel ICBMs launched from locations between 25 and 45 degrees north latitude and would use a shoot-shoot engagement strategy. The capability envisioned for Option 5 would require about 15 medium-lift launch vehicles to place 156 SBIs in orbit.

CBO's Estimating Methods

The costs for the BPI systems in CBO's options can be divided into three categories:

- Research and development (R&D)—the engineering activities needed to design and develop the booster, kill vehicle, and other components that make up a BPI system. The R&D phase also involves testing the hardware to ensure that it works and integrating the BPI system into the military's existing infrastructure and support elements (for example, making sure the communications equipment for the BPI system can "talk to" that of other DoD units).
- Production—the manufacturing of interceptors and associated support equipment and, for the space-based options, the purchasing of launch services.
- Operations—the routine efforts to maintain, operate, and replenish a BPI system over 20 years.

The rest of this appendix discusses the methods that CBO used to estimate all three types of costs. Production costs are described before R&D costs because some of the methods for calculating R&D costs use estimates of production costs as inputs.

Production Costs

Production costs for the surface-based options would total between $3.4 billion and $7.4 billion, CBO estimates, and costs for the space-based options would total between $5.2 billion and $21.7 billion (see Tables A-1 and A-2). In general, CBO developed those estimates by calculating the number of interceptors that each option would require and tallying their purchase costs. CBO also determined how much the other components of each BPI system would cost, including launch services to place the space-based interceptors into orbit.

Interceptors. An interceptor consists of a booster and a kill vehicle with a seeker (basically, one or more sensors).[4] Surface-based systems include a canister for each interceptor as well, to protect it from the elements; space-based systems use the interceptor life jacket. CBO's estimates of the costs for each option's interceptors include costs to buy those components as well as costs to integrate and assemble them into a BPI system.

CBO assumed that for each of the three surface-based options, DoD would purchase a total of 112 interceptors (60 for routine operations, 12 for spares, and 40 for system testing). Under Option 4, 405 space-based interceptors would be bought (368 for routine operations and 37 for spares), and under Option 5, 172 interceptors (156 for operations and 16 for spares). For the two space-based alternatives, CBO assumed that DoD would not pur-

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[3] The northernmost point in North Korea actually lies at about 43 degrees north latitude. However, intercepts of North Korean ICBMs fired toward the continental United States would have to occur farther north.

[4] For more information about kill vehicles and their components, see Appendix B.

Table A-3.

Estimated Costs of the First Production Units for Surface-Based BPI Systems

(Millions of 2004 dollars)

	Option 1 (6-km/sec interceptors)		Option 2 (8-km/sec interceptors)		Option 3 (10-km/sec interceptors)	
Cost Category	**Low**	**High**	**Low**	**High**	**Low**	**High**
Booster	15.1	20.8	17.4	24.1	35.5	49.0
Kill Vehicle	12.2	14.5	12.2	14.5	12.2	14.5
Seeker	1.1	1.4	1.1	1.4	1.1	1.4
Canister	1.4	1.9	1.4	1.9	1.4	1.9
Integration and Assembly	3.6	4.6	3.9	5.0	6.0	8.0
Total	**33.4**	**43.2**	**36.0**	**46.9**	**56.3**	**74.8**

Source: Congressional Budget Office.

Notes: To produce the high estimates, CBO applied cost-growth factors to the low estimates. Those factors (38 percent for the booster and canister and 19 percent for the kill vehicle and seeker) were prepared by the RAND Corporation on the basis of unpublished updates to a 1996 RAND report, *The Defense System Cost Performance Database: Cost Growth Analysis Using Selected Acquisition Reports.* No cost-growth factor was applied to integration and assembly costs, which were estimated at 12 percent of the booster, kill-vehicle, seeker, and canister costs for both the low and high estimates.

BPI = boost-phase intercept; km/sec = kilometers per second.

chase any test interceptors (beyond those used during the R&D stage) because aging operational interceptors could be used for any required testing as they neared the end of their service lives.

CBO calculated total production costs for each option's interceptors using a two-step approach. Analysts first estimated the costs of producing the first unit of each of the interceptor's components. They then projected those costs for the rest of the purchases planned under the option, using learning-curve methods to account for the effects of quantity on unit production costs.[5]

Purchase of the First Interceptor. Various methods were used to gauge the costs for producing the first unit of each of the interceptor components. (All such estimates include a profit margin for the manufacturer and an allowance for systems engineering and program management.)

- For the booster, CBO used a cost-estimating relationship (CER) developed by Technomics that employs a booster's total impulse, expressed in newtons of thrust times seconds of burn time, to predict its first-unit production costs.[6]
- For the canister (used only in surface-based interceptors), costs were based on estimates from MDA.
- For the kill vehicle and (in the case of space-based interceptors) the life jacket, CBO used a CER developed by Tecolote based on a space vehicle's weight (in this case, the weight of the kill vehicle or life jacket) to separately estimate production costs for those two components.[7]
- For the costs of the kill vehicle's seeker, CBO used a proxy: actual costs for the seeker that will be deployed on the newest version of the Navy's Standard missile.

Assembling the components would add 12 percent to those costs, CBO estimated—a percentage that is on a par with Tecolote's CER for such work.

On the basis of those calculations, CBO estimated that for Option 1, the first interceptor off the production line would cost about $33 million (before any upward adjustments were made to reflect potential cost risk, the possi-

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[5] Learning-curve methods theorize that as more interceptors are built, the unit price of each subsequent production lot falls by a fixed percentage.

[6] Technomics, Inc., *National Missile Defense Propulsion Cost Estimating Relationships* (Santa Barbara, Calif.: Technomics, August 2000).

[7] Tecolote Research, Inc., *The Unmanned Space Vehicle Cost Model*, 8th ed. (Goleta, Calif.: Tecolote Research, June 2002).

Table A-4.

Estimated Costs of the First Production Units for Space-Based BPI Systems

(Millions of 2004 dollars)

	Option 4 (4-km/sec interceptors)		Option 5 (6-km/sec interceptors)	
Cost Category	**Low**	**High**	**Low**	**High**
Booster	7.8	10.8	5.8	8.1
Kill Vehicle	12.2	14.5	12.2	14.5
Seeker	1.1	1.4	1.1	1.4
Life Jacket	6.6	7.9	6.6	7.9
Integration and Assembly	3.3	4.1	3.1	3.8
Total	**31.1**	**38.7**	**28.9**	**35.7**

Source: Congressional Budget Office.

Notes: To produce the high estimates, CBO applied cost-growth factors to the low estimates. Those factors (38 percent for the booster and 19 percent for the kill vehicle, seeker, and life jacket) were prepared by the RAND Corporation on the basis of unpublished updates to a 1996 RAND report, *The Defense System Cost Performance Database: Cost Growth Analysis Using Selected Acquisition Reports.* No cost-growth factor was applied to integration and assembly costs, which were estimated at 12 percent of the booster, kill-vehicle, seeker, and life-jacket costs for both the low and high estimates.

BPI = boost-phase intercept; km/sec = kilometers per second.

bility that production costs might exceed CBO's estimates). Using the same methods, CBO calculated that the first interceptor for Option 2 would cost $36 million; for Option 3, $56 million; for Option 4, $31 million; and for Option 5, $29 million (see Tables A-3 and A-4).

To account for cost risk, CBO applied to each of its estimates for the interceptor's components factors that reflected historical cost growth for comparable systems. For example, on the basis of information reported by the RAND Corporation, CBO estimated that production costs for the booster and canister could grow by about 38 percent and that production costs for the kill vehicle, seeker, and life jacket could rise by about 19 percent.

Subsequent Purchases of Interceptors. Costs for the rest of the interceptors that would be purchased under each option were estimated by analyzing the trends in actual costs for the Ground-Based Midcourse Defense system interceptor that MDA is now purchasing and plans to deploy later this year. CBO's analysis indicated that by doubling the quantity being purchased, unit costs could be reduced by about 5 percent. Buying the 112 interceptors called for under Option 1 would result in an average cost per interceptor of about $25 million, according to CBO's low estimate. Total interceptor production costs under Option 1 would range from $2.8 billion (without taking cost risk into account) to $3.6 billion (with cost risk).

CBO used the same learning-curve method to estimate total interceptor production costs for the remaining options. Producing 112 of Option 2's interceptors would cost between $3.1 billion and $4.0 billion, and producing the same number of Option 3's interceptors would cost $4.8 billion to $6.4 billion (see Table A-1). For the space-based systems, production costs for the 405 interceptors in Option 4 would total between $8.7 billion and $10.7 billion, CBO estimated, compared with $3.7 billion to $4.6 billion for the 172 interceptors in Option 5 (see Table A-2).

Other Components. In addition to interceptors, each of the surface-based options would require either 30 or 60 mobile launchers, 10 sets of C2BMC equipment (one at each site), and three cargo ships. Options 1 and 2 envision using 30 mobile launchers, each configured to launch two interceptors; Option 3 would require 60 mobile launchers because each launcher would be able to fire only one of the larger interceptors used in that alternative.

The space-based options would require not mobile launchers but rather launch vehicles to carry the interceptors into orbit. The number of launches necessary to deploy the space-based interceptors under each option would depend on the payload lift capability of the launch vehicle and the total mass of the constellation of interceptors. By CBO's estimates, the interceptors in Option 4 would be most efficiently launched by heavy-lift launch vehicles, and those in Option 5 by medium-lift vehicles. Option 4's constellation would have about six times more mass than Option 5's because it would include nearly three times as many interceptors and each interceptor would weigh nearly twice as much.

Using those weight calculations and lift capacities, CBO estimated that Option 4 would require 28 launches using heavy-lift launch vehicles, and Option 5 would require 15 launches using medium-lift vehicles. CBO assumed that those options could forgo C2BMC equipment because the interceptors would rely on existing space-related command and communications facilities, such as those located in Colorado at Cheyenne Mountain or Schriever Air Force Base.

In the surface-based options, production costs for components other than interceptors would make up a relatively modest share of each option's total costs. Costs for other components required under both Option 1 and Option 2 would total about $0.6 billion ($0.3 billion for mobile launchers, $0.2 billion for cargo ships, and $0.1 billion for C2BMC equipment). Those costs would be slightly higher in Option 3 (by about $0.2 billion) because of the 30 additional mobile launchers (see Table A-1).

In the space-based options, launch services would cost between $7.3 billion and $11.0 billion for Option 4, CBO estimates, and between $1.5 billion and $2.3 billion for Option 5 (see Table A-2). CBO based its estimates on the price of launch services today, deriving a cost of about $11,000 per kilogram of payload lift capacity. Applying that factor, CBO estimated that a launch on a medium-lift vehicle—one with a lift capacity of 8,300 kg (8.3 metric tons, or tonnes)—would cost about $100 million. (That cost covers both the vehicle itself and its launching of the interceptor into orbit). A launch on a heavy-lift vehicle—one with a lift capacity of 23 tonnes—would cost about $250 million.

On the basis of information reported by the RAND Corporation, CBO estimated that cost growth for other components of a BPI system could amount to about 38 percent for mobile launchers, about 13 percent for C2BMC equipment, and about 20 percent for cargo ships.[8] For the launch vehicles, CBO calculated a cost-growth factor of about 50 percent on the basis of the costs for existing vehicles, such as the Delta II, Atlas II, and Titan IV systems.

Research and Development Costs

CBO estimated that R&D would cost between $6.7 billion and $19.5 billion for the surface-based BPI options and between $7.1 billion and $12.9 billion for the space-based options. To arrive at those numbers, CBO's general method was to estimate how much it would cost to develop the BPI system in Option 1, calculating development costs for each major element (the booster, the kill vehicle, and the other components) as well as costs for testing, evaluation, and system integration (the top-level engineering and management efforts needed to support the detailed design work of the R&D phase). CBO then estimated costs for the remaining options by adjusting the Option 1 figures to reflect technological hurdles inherent in the other alternatives. For options that would require significant advances in technology relative to that envisioned for Option 1, CBO increased the costs. For options that represent less-robust technology, CBO lowered the costs.

Boosters. On the basis of information provided by MDA, CBO estimated that R&D costs for the booster that Option 1 would deploy would total about $2.2 billion—approximately half of CBO's recent estimate of R&D costs for the Ground-Based Midcourse Defense system interceptor. CBO considered MDA's data a more reasonable starting point than its estimate because the BPI system would probably be slower than the midcourse system and use more "off-the-shelf" components in its production.

For boosters in the other surface-based options, CBO assumed that their research and development costs would be proportional to their production costs. Using the ratio of the first-unit production costs for the surface-based boosters as a proxy, CBO estimated that developing the booster for Options 2 and 3 would cost $2.5 billion and $5.3 billion, respectively (without cost growth).

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[8] Jeanne M. Jarvaise, Jeffrey A. Drezner, and D. Norton, *The Defense System Cost Performance Database: Cost Growth Analysis Using Selected Acquisition Reports*, MR-625-OSD (Santa Monica, Calif.: RAND Corporation, 1996). The cost-growth factors that CBO used in its analysis were based on unpublished updates of that report.

For the SBI boosters, CBO also used the ratio of the first-unit production costs as a proxy. It estimated that booster development for Options 4 and 5 would cost $1.2 billion and $0.9 billion, respectively. CBO then increased those costs by a factor of 2.3, bringing the estimates to $2.7 billion for Option 4 and $2.0 billion for Option 5. That factor was applied to account for the cost risk associated with developing space-based systems that incorporate technologies designed for surface-based operations. It was based on the cost growth of analogous hardware—specifically, the estimated R&D costs of a space-based radar program (about $9 billion) and the actual costs of the JSTARS radar program (about $4 billion).

CBO also derived estimates for booster R&D that accounted for the risk of cost growth. Those estimates range from $3.1 billion to $7.4 billion for the surface-based options and $2.9 billion to $3.8 billion for the space-based options. Analysts applied a factor of 41 percent to reflect historical cost growth for earlier booster development programs, such as for the Minuteman and Trident missiles.

Kill Vehicles. Developing the kill vehicle used in Options 1 and 4 would cost a total of $0.5 billion to $0.8 billion, CBO estimates—a relatively small amount compared with the cost of developing the kill vehicle that MDA plans to use with its midcourse interceptors. The reason for the lower cost is that a BPI system would benefit from that previous development effort by using existing or modified components to reduce R&D costs.

CBO assumed that Options 2, 3, and 5 would require development of a new, miniaturized kill vehicle. Although production costs for that kill vehicle were assumed to be the same as for the heavier 140-kg vehicle, CBO estimated that R&D costs would be higher because new technologies would be needed to make the kill vehicle smaller but just as effective. Using information from Lawrence Livermore, CBO estimated that designing a miniaturized kill vehicle would cost about $300 million; a program of five integrated flight tests and several ground tests would boost those costs by $750 million. In CBO's estimation, after adding allowances for profits and project management and systems engineering, developing a miniaturized kill vehicle would cost about $1.7 billion to $2.9 billion (assuming a factor of 69 percent to account for historical cost growth in space programs).

Other Components. CBO used information from MDA to estimate R&D costs for the other components of a BPI system. Those costs would total about $1.2 billion (without cost growth) for each of the surface-based options: $0.2 billion for the canister, $0.3 billion for the mobile launcher, and $0.7 billion for C2BMC equipment. For the space-based options, R&D costs for other components would total $1 billion in the case of Option 4 and $1.6 billion in the case of Option 5. Those figures include $0.7 billion for C2BMC equipment as well as $0.3 billion for the life jacket in Option 4 and $0.9 billion for the life jacket in Option 5.

To account for cost risk, CBO increased those low estimates by factors ranging from 31 percent to 69 percent—depending on the historical cost growth for each type of component. Those high estimates range from $1.6 billion for the surface-based options to between $1.3 billion and $2.4 billion for the space-based alternatives.

Test and Evaluation. Costs for testing and evaluation cover the hardware needed to conduct integrated flight tests and the analysis required to evaluate those tests. On the basis of information from MDA, CBO assumed that the test and evaluation program for Option 1 would consist of five integrated flight tests and that conducting and evaluating those tests would cost a total of about $0.9 billion. For the other options, CBO assumed that test and evaluation costs would vary with the first-unit production costs of the interceptors and would total between $0.8 billion and $1.4 billion. The estimates that account for cost risk range between $1.0 billion and $2.0 billion for all of the options, reflecting the historical cost growth of analogous hardware.

System Integration. CBO assumed that system integration would add 40 percent to the total costs for interceptors, other components, and the test and evaluation phase—a percentage consistent with the costs for programs that deploy complex state-of-the-art technologies, such as MDA's midcourse interceptor. Costs for system integration range from $1.9 billion to $5.6 billion, CBO estimates.

Operations Costs

In general, CBO estimated the routine costs for operating the BPI systems for a 20-year period as well as the costs for conducting periodic tests of the interceptors during operations (to ensure that they remained effective and safe) and for providing continual engineering support.

For the space-based options, CBO also estimated how much it would cost to buy replacement interceptors and launch them into orbit. Twenty years' operation of the surface-based BPI systems would cost between $5.6 billion and $9.7 billion, compared with $13.4 billion to $46.3 billion for the space-based systems.

Routine Operations. For Options 1 through 3, CBO assumed that the surface-based BPI systems would be operated similarly to the Army's Patriot missile units. Each launch site would require about 100 people, operating three to six mobile launchers and one set of C2BMC equipment. (CBO based those assumptions on information provided by MDA.) Judging from the Patriot units, each site would cost about $10 million a year to operate, CBO estimates. Over 20 years, operating 10 sites would cost a total of about $1.8 billion (without cost growth).

For the space-based options, CBO analyzed the actual costs of operating the Global Positioning System (GPS)—a constellation of 24 satellites. (Its size makes its operational challenges analogous to those confronting the operators of a BPI system.) On the basis of that comparison, CBO estimated that operating a constellation of space-based interceptors would cost about $50 million a year under either Option 4 or Option 5 and would total about $1 billion over a 20-year span.

To account for the uncertainty in all such estimates—and to capture that uncertainty in the assumptions it used to develop the estimates for routine operations costs—CBO applied a cost-growth factor of 50 percent for the surface-based BPI systems and a cost-growth factor of 100 percent for the space-based systems. The resulting high estimates of routine operations costs were $2.7 billion and $2.0 billion, respectively. The cost-growth factor was larger for the space-based interceptors because of the greater uncertainty attached to the assumption that a constellation consisting of as many as 368 interceptors would cost the same amount to operate as a constellation of 24 GPS satellites.

Estimated costs to operate the cargo ships that would deploy some of the surface-based interceptors were based on actual costs to operate Navy logistics support ships. In CBO's estimation, an inventory of three ships would be necessary to ensure that two were continually available. Operating those ships would cost a total of about $90 million a year, CBO estimates, and $1.8 billion over 20 years. CBO used those amounts for its high estimates—a departure from its estimating method for other components, in which it first established the low estimate and then determined the high estimate on the basis of historical cost growth. In the case of the cargo ships, CBO decreased the above costs by 33 percent to arrive at a low estimate that reflected a slower operating tempo than that of logistics support ships.

Operational Tests. In general, operational tests have three components: the targets that are launched to simulate enemy missiles, the interceptors that are fired at those targets, and the analysis of the data from the test. CBO assumed that for any of the BPI systems, MDA would conduct a total of 40 operational tests over the 20-year period of this analysis. Using information from MDA, CBO estimated that each test would cost about $40 million—about $20 million for the targets and their launch services and another $20 million for data analysis. Thus, 40 operational tests over 20 years would cost $1.6 billion, CBO estimates. (Costs for operational testing would be the same in the space-based options as in the surface-based alternatives because the tests of SBIs would use the same target set and employ similar analyses as the tests of surface-based interceptors.) The costs of the interceptors used in the tests are classified as production costs and thus are not included here.

In taking cost uncertainty into account, CBO incorporated assumptions that the costs for the targets could increase to $40 million each (to allow MDA to test the interceptor against more-sophisticated threats) and that the costs for analyzing the additional data could rise to $40 million as well. On the basis of those assumptions, CBO estimated that the cost of operational testing would increase twofold, to about $3.2 billion.

Ongoing Operational Integration. After the BPI systems were deployed, some engineering work would continue during their operational life to resolve problems and incorporate new technologies. CBO assumed that MDA would retain a cadre of about 200 engineers to provide that support. Such ongoing operational integration would cost about $50 million a year, CBO estimated, or about $1 billion over 20 years. For comparison, CBO looked at the average annual spending expected to occur during the R&D phase. Under Option 1, CBO estimated that MDA would spend $6.7 billion over an eight-year span in the R&D phase, or about $800 million a year; $50 million is slightly less than 10 percent of that annual average. CBO's higher estimate for ongoing operational integration (to account for cost uncertainty) was $2 billion for the 20-year period.

Replacement of Space-Based Interceptors. CBO assumed that the space-based interceptors in Options 4 and 5 would have a life span of about seven years. Thus, over the 20-year period considered in this analysis, they would need to be replaced two or three times to sustain the system's effectiveness.

CBO estimated the costs for replacement interceptors in the same way that it calculated the costs for producing the first interceptor under each option. For Option 4, replacement interceptors would cost a total of $16 billion to $20 billion, and for Option 5, between $7 billion and $9 billion. MDA would also need to purchase additional launch services to put the new interceptors into orbit. In CBO's estimation, the costs for those services would total between $13 billion and $19 billion for Option 4 and between $3 billion and $4 billion for Option 5. CBO's high estimates reflect historical cost growth for satellite systems, boosters, and launch services.

APPENDIX

B

Kinetic Kill Vehicles for Boost-Phase Interceptors

The type of kinetic-energy interceptors described in this report consist primarily of a rocket booster and a kill vehicle. The booster accelerates its kill vehicle to a high velocity and carries it toward the predicted intercept point. The booster is jettisoned after its fuel is expended, and the kill vehicle completes the engagement. As the intercept point approaches, the kill vehicle must identify its target using onboard sensors and then correct its course to achieve a hit. This appendix briefly discusses the two primary components of a kinetic-energy kill vehicle—sensors for target identification and tracking, and a divert and attitude control system (DACS) for maneuvering.

Sensors

The "eyes" of a kill vehicle typically include seekers (basically, one or more sensors) that "acquire" the target and help guide the vehicle to the final intercept point. Seekers may be active or passive. Passive seekers exist for a broad portion of the electromagnetic spectrum, including short-, medium-, and long-wave infrared as well as ultraviolet and visible wavelengths. Active seekers may include conventional radar or laser imagers or rangers.

The selection of a seeker depends on the characteristics of the target. For example, a midcourse seeker must detect relatively small, cold warheads moving above the atmosphere and distinguish them from decoys that might be deployed to fool missile defenses. In contrast, a boost-phase seeker has the seemingly simple task of homing in on a very hot, bright ballistic missile rocket. During the boost phase, however, a ballistic missile's signature comprises both the missile body itself and the large rocket plume. At high altitudes, the plume "blooms" around the missile—in effect, creating a smoke screen of hot exhaust gas that, depending on the kill vehicle's angle of approach, can obscure the body of the rocket. A kill vehicle must be able to detect and hit the missile within the plume.

That so-called plume/hard-body problem could be solved in several ways. One would be to select a single sensor wavelength band and combine it with signal processing to distinguish the plume from the missile. Although that idea is attractive in principle—a one-color seeker is likely to be simpler and less expensive than other alternatives—in practice, the electromagnetic signature of a ballistic missile in the boost phase may be too complex for that method to be successful. The Missile Defense Agency plans to conduct the Near-Field Infrared Experiment (NFIRE) to better understand the characteristics of that signature for intercontinental ballistic missiles (ICBMs).

The information that NFIRE might provide would also be helpful in relation to a second alternative: the use of a multicolor seeker sensitive to two or more wavelength bands. Although both a missile and its plume are hot and bright, they have different spectral characteristics. If signal processors could operate in two or more wavelength bands, they might be able to subtract the plume's contribution to the image seen by the seeker from that of the missile, leaving behind only the missile's characteristics for targeting. However, a multicolor seeker suitable for use in boost-phase interceptors would be more difficult and costly to produce than a one-color seeker.

A third approach to differentiating between the plume and the hard body would be to augment a passive seeker with an active seeker to detect the missile body in the "end game" (the time just before the kill vehicle hits its target). Light detection and ranging (lidar) systems that use a laser to penetrate the plume and locate the missile body have been proposed for that application. However, a lidar system's potential to improve the probability of hitting the target must be weighed against its disadvantages, which include increased complexity, weight, and costs relative to other alternatives.

The Maneuvering System

The other primary component of a kill vehicle is the DACS—the propulsion package that not only gives the vehicle maneuvering capability for the intercept but also keeps it balanced and pointing in the right direction. The maneuverability that the DACS provides is typically measured in terms of divert velocity. As with the seekers, the capabilities needed from the DACS depend on the behavior of the target and the accuracy of the interceptor's tracking. In general, the greater the total course correction needed to keep a kill vehicle directed toward its target, the greater the divert velocity the vehicle requires. The predictable ballistic trajectories of midcourse targets allow the use of kill vehicles with relatively low divert velocities—typically less than 1 kilometer per second (km/sec). During the boost phase, however, a target missile's trajectory may be more uncertain. For boost-phase intercept, conclusions from a study by the American Physical Society, as well as similar (unpublished) results from engineers at Lawrence Livermore National Laboratory, support the view that intentional evasive maneuvers (if any) by an ICBM or unintentional variations in its thrust can require that a kill vehicle have greater divert capability—perhaps as much as 2.5 km/sec.[1] But a higher-performance DACS usually comes at the expense of greater weight, because larger thrusters are needed as well as more fuel (and the tanks to hold it).

A DACS can be of either the solid- or liquid-fuel type, and liquid-fuel designs can be either pressure- or pump-fed. Most existing kill vehicles use pressure-fed liquid propellant, although the Navy is testing a solid-fuel DACS (which will be compatible with shipboard safety restrictions) for its SM-3 missile. Pressure-fed systems are simpler than pump-fed designs but require heavier propellant tanks and larger nozzles and combustion chambers. Pump-fed systems, such as those being developed by Lawrence Livermore, are more complex mechanically than pressure-fed systems of a similar mass, but they also offer greater divert velocity. Despite some testing of pump-fed concepts, the Department of Defense has announced no plans for their operational use. Thus, to specify the use of pump-fed systems in liquid-fuel DACS designs would pose greater technological challenges than would specifying the use of a pressure-fed system.

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1. See *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues* (Washington, D.C.: American Physical Society, July 2003), available at www.aps.org/public_affairs/popa/reports/nmd03.cfm. Engineers at Lawrence Livermore National Laboratory communicated similar but unpublished conclusions to CBO staff.

Glossary of Abbreviations

ABM: Anti-Ballistic Missile (Treaty)

APS: American Physical Society

BMD: ballistic missile defense

BMDS: ballistic missile defense system

BPI: boost-phase intercept

C2BMC: command, control, battle management, and communications

CBO: Congressional Budget Office

CER: cost-estimating relationship

DACS: divert and attitude control system

DoD: Department of Defense

g: a unit of force equal to the Earth's gravitational pull

ICBM: intercontinental ballistic missile

I_{sp}: specific impulse

kg: kilogram

km: kilometer

MDA: Missile Defense Agency

NFIRE: Near-Field Infrared Experiment

NMD: national missile defense

PAC-3: Patriot Advanced Capability-3

R&D: research and development

SBI: space-based interceptor

SBIRS: Space-Based Infrared System

SLV: space-launch vehicle

THAAD: Terminal High Altitude Air Defense