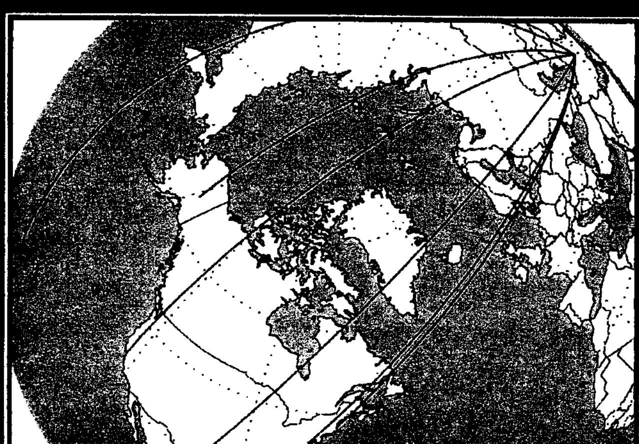
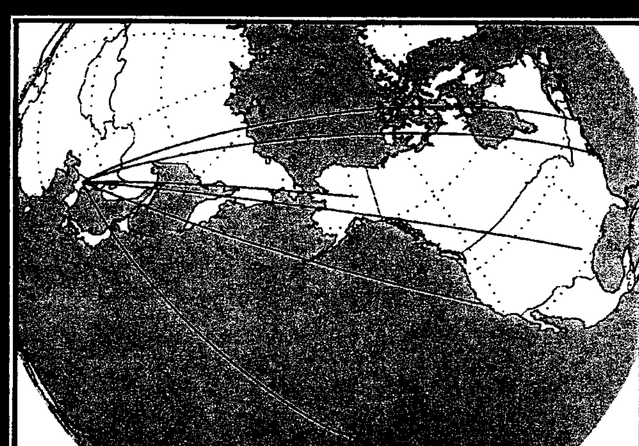
Report of the APS Study Group on Boost-Phase Intercept Systems for National Missile Defense

Executive Summary and Findings

AMERICAN PHYSICAL SOCIETY





Report of the
American Physical Society Study Group on

Boost-Phase Intercept Systems for National Missile Defense

Scientific and Technical Issues

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EXECUTIVE SUMMARY AND FINDINGS

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Preface

The American Physical Society (APS) is the largest society for professional physicists in the United States, with more than 40,000 members. The principal functions of the APS are overseeing the publication of professional journals and arranging scientific meetings. The APS also assists the physics community through educational and public outreach programs. In addition, from time to time the APS produces reports on matters of public interest that require technical understanding, and for which an impartial and authoritative analysis would be of particular use to the public and to policy makers. The last such report was on the use of directed energy weapons for missile defense.[1] This is another report in that tradition.

[1] Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons, *Rev. Mod. Phys.*, Vol. 59, No. 3, Part II, 1987.

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Executive Summary

Boost-phase intercept systems for defending the United States against ballistic missile attack are being actively considered as a major part of a national missile defense strategy. Spending on such systems by the U.S. Department of Defense is growing, and there is a prospect of much larger expenditures in the future. Boost-phase intercept weapons would seek to disable attacking missiles during the first few minutes of flight, while the missiles' boosters are still burning and before they have released nuclear, chemical, or biological munitions. The technical aspects and feasibility of such weapons are the subject of this report.

In spite of the growing interest in boost-phase intercept systems and the increasing resources being committed to developing them, little quantitative information about their technical feasibility, required performance, and potential advantages and disadvantages is available to the public. Consequently, the American Physical Society (APS) convened a study group of physicists and engineers, including individuals with expertise in sensors, missiles, rocket interceptors, guidance and control, high-powered lasers, and missile-defense-related systems, to assess the technical feasibility of boost-phase intercept systems.

The Study Group has based its assessments solely on information found in the open literature about ballistic missiles and missile defense. We have supplemented this information by our expertise in science and engineering and have confined the assessments reported here to those that can be made with confidence by applying the fundamental principles of rocket propulsion, signal detection and processing, guidance and control, and laser beam propagation. In many instances, as documented throughout this report, we have performed our own analyses to address important issues and to assure ourselves of the validity of our conclusions.

Our main conclusions are the following:

1. **Boost-phase defense against intercontinental ballistic missiles (ICBMs) hinges on the burn time of the attacking missile and the speed of the defending interceptor rocket. Defense of the entire United States against liquid-propellant ICBMs, such as those deployed early by the Soviet Union and the People's Republic of China (China), launched from countries such as the Democratic People's Republic of Korea (North Korea) and Iran, may be technically feasible using terrestrial (land-, sea-, or air-based) interceptors. However, the interceptor rockets would have to be substantially faster (and therefore necessarily larger) than those usually proposed in order to reach the ICBMs in time from international waters or neighboring countries willing to host the interceptors. The system would also require the capability to cope with at least the simplest of countermeasures.**

2. **Boost-phase defense of the entire United States against solid-propellant ICBMs, which have shorter burn times than liquid-propellant ICBMs, is unlikely to be practical**

when all factors are considered, no matter where or how interceptors are based. Even with optimistic assumptions, a terrestrial-based system would require very large interceptors with extremely high speeds and accelerations to defeat a solid-propellant ICBM launched from even a small country such as North Korea. Even such high-performance interceptors could not defend against solid-propellant ICBMs launched from Iran, because they could not be based close enough to disable the missiles before they deployed their munitions.

3. **If interceptor rockets were based in space, their coverage would not be constrained by geography, but they would confront the same time constraints and engagement uncertainties as terrestrial-based interceptors. Consequently, their kill vehicles (the final homing stage of the interceptors) would have to be similar in size to those of terrestrial-based interceptors. With the technology we judge could become available within the next 15 years, defending against a single ICBM would require a thousand or more interceptors for a system having the lowest possible mass and providing realistic decision time. Deploying such a system would require at least a five- to tenfold increase over current U.S. space-launch rates.**

4. **The Airborne Laser now under development could have some capability against liquid-propellant missiles, but it would be ineffective against solid-propellant ICBMs, which are more heat-resistant.**

5. **The existing U.S. Navy Aegis system, using an interceptor rocket similar to the Standard Missile 2, should be capable of defending against short- or medium-range missiles launched from ships, barges, or other platforms off U.S. coasts. However, interceptor rockets would have to be positioned within a few tens of kilometers of the launch location of the attacking missile.**

6. **A key problem inherent in boost-phase defense is munitions shortfall: although a successful intercept would prevent munitions from reaching their target, it could cause live nuclear, chemical, or biological munitions to fall on populated areas short of the target, in the United States or other countries. Timing intercepts accurately enough to avoid this problem would be difficult.**

The Charge

Boost-phase missile defense systems would disable attacking missiles while their rocket motors are burning by hitting them with an interceptor rocket or a laser beam. For ICBMs, this phase of flight typically lasts 3 or 4 minutes. Boost-phase defense has been proposed as a way to avoid the problems faced by midcourse defense systems, which are intended to disable the attacking missile's warheads after they have been deployed. The midcourse approach is complicated by the need to counter multiple warheads, submunitions ("bomblets"), lightweight decoys, and other countermeasures.

The Study Group was asked to evaluate boost-phase intercept systems that would defend the United States using land-, sea-, air-, or space-based interceptor rockets or an airborne laser now being developed. Space-based laser systems were not included because the technology needed for such systems would not be ready within the 10- to 15-year period considered. The Study did not consider the feasibility of the communications, command, control, and battle management that would be required. Nor did it consider policy issues, such as the arms control, strategic stability, or foreign policy implications of testing or deploying a boost-phase defense.

The Focus

Developing and deploying a reliable boost-phase missile defense would be a major undertaking likely to require a decade or more to complete. We therefore considered missiles that might be developed or acquired by North Korea and Iran during the next 10 to 15 years. These countries were the focus of the Study because the U.S. government has expressed concern specifically about them. According to U.S. intelligence estimates, neither of them currently has a credible ICBM capability but they are projected to develop or acquire ICBMs within the next 10 to 15 years. The Study Group also considered defense against ICBMs launched from Iraq. With the changed political situation arising from the events of the Spring of 2003, an ICBM threat from Iraq appears unlikely for the foreseeable future. We have nevertheless retained the analysis of the Iraq threat in the body of our report, to illustrate the requirements for defending against ICBMs from a country that is intermediate in size between North Korea and Iran.

We began by identifying boost-phase intercept systems that could work in principle and then determined the system performance that would be required to defend the entire United States, the contiguous 48 states, or only the largest U.S. cities. The attacking missiles were assumed to be similar to the first ICBMs developed 30 to 40 years ago by the United States, the Soviet Union, and China. Both liquid- and solid-propellant missiles were considered, because either type could be developed or acquired within 10 to 15 years.

Key Issues

Hitting the Missile. An important question in boost-phase defense is whether the kill vehicle carried by the interceptor could actually hit a long-range missile, given the inherently unpredictable acceleration that is normal for an ICBM in powered flight and the possibility of programmed trajectory-shaping or evasive maneuvers. Assuming interceptors can reach the missile during its boost phase, we find no fundamental obstacle to homing on the missile accurately enough to hit it. To do so, however, the kill vehicle would have to be very agile and would need to carry enough fuel to continue adjusting to the missile's acceleration until the moment of impact. We determined that kill vehicles capable of meeting these requirements would be substantially heavier than those that some have suggested for boost-phase intercept. Our analysis of this agility requirement and its implications for the weight of the interceptor are key new aspects of this study.

Time. Time is short for boost-phase defense because ICBMs burn out quickly: in roughly 3 minutes for solid-propellant missiles and 4 minutes for liquid-propellant missiles. But the time actually available is substantially shorter than the duration of the burn. Even systems with state-of-the-art tracking sensors would require 45 to 65 seconds or longer to detect the launch of a potentially threatening rocket and determine its direction of flight well enough to fire an interceptor (that is, obtain a firing solution).

Additional time must also be allowed for the decision to fire. We have analyzed the decision times that would be provided by various boost-phase defenses. "Decision time" as used here also includes any additional time required for communication between system elements, estimating the performance characteristics of the attacking missile and its trajectory, resolving uncertainties in the performance of the defense system, and other operational factors.

To be successful, the intercept would have to occur before the missile gives its munitions the velocity needed to reach the United States. This velocity could be attained as early as 40 seconds before the missile would normally burn out.

Due to the potentially similar flight profiles of ICBMs and space launchers, in many cases the defense system would not be able to distinguish a peaceful space launch from an ICBM attack. In these cases, the defense would have to shoot at every rocket, unless it had been established as nonthreatening before it was launched.

Extending the time for intercept beyond the boost phase into the ascent phase (defined here as the period after the missile's final stage has burned out or its thrust has been terminated but before it has deployed all its munitions and decoys) would not increase the available time significantly. The reason is that once the missile's thrust has been terminated, it could deploy its munitions and any decoys or countermeasures quickly, possibly in less than a second.

With so little time available, interceptors would need to reach high speeds very quickly. Taken together, the short time available for intercept and the size of the kill vehicle needed to hit an unpredictably accelerating ICBM would require large interceptors. In some cases, they would have to be larger and faster than the ICBMs themselves and would have to accelerate four times more quickly. Such interceptors have never been built and would push the state of the art.

Range. The useful range of interceptor rockets is restricted by practical limits on rocket speeds and by the short time available for intercepting the attacking missile. The range of the Airborne Laser is also limited, both by constraints on its power and by the distance its beam can propagate through the atmosphere and remain focused. Consequently, boost-phase defense would be possible using interceptor rockets only if they could be positioned close enough to the required intercept locations, generally within 400 to 1000 kilometers. Defense would be possible using the Airborne Laser only if it could be stationed within 300 to 600 kilometers of the intercept points. The required intercept locations are typically hundreds of kilometers downrange from the missile launch site, which would further restrict interceptor basing options.

In general, boost-phase defense using terrestrial (land-, sea-, or air-based) rocket interceptors or the Airborne Laser requires that the missile's flight path during its boost phase be accessible from international waters or from neighboring countries willing to host U.S. interceptors. The feasibility of boost-phase defense therefore depends not only on the performance of the attacking missile and the speed of the interceptor, but also on the size of the country that launches the missile, the direction of the missile's flight, and the local physical and political geography.

Shortfall. If a missile were hit during its boost phase by an interceptor, it would probably lose thrust quickly, but the missile (perhaps in fragments) and its munitions would not fall straight down. Instead they would continue on ballistic trajectories, falling to Earth short of their target but possibly on populated areas. Thus, unless the missile's munitions were disabled by the collision—which cannot be assumed because they are loosely coupled to the missile and hardened to withstand re-entry at hypersonic speeds—a successful intercept could cause live munitions to fall on populated areas. These areas would not be in the attacking country but might well be in countries friendly to the United States or in the United States itself.

This problem is inherent in boost-phase intercept. Our analysis indicates that it would be extremely difficult to time intercepts to avoid causing live munitions or debris to hit populated areas. This problem would be eliminated if the interceptor could reliably destroy the missile's munitions, but doing so would be much more difficult than simply disabling the missile's booster rocket.

Space-Based Interceptor Requirements. Boost-phase interceptors fired from orbiting satellites could in principle defend the United States against ICBMs launched from anywhere on Earth. While their coverage would not be constrained by geography, space-based interceptors would have the same time constraints and engagement uncertainties as terrestrial-based interceptors. As a result, their kill vehicles would have to be at least as massive as the kill vehicles of terrestrial-based interceptors. Because a satellite orbiting at low altitude spends so little time over a single spot on Earth, many interceptor-carrying satellites would be needed to defend against even a single missile. The precise number of satellites and the total mass that would have to be placed into orbit would depend on the type of ICBM as well as the speeds, accelerations, and masses of the interceptors and their kill vehicles, which would in turn depend on the technology available. Based on the technology that could, in our judgment, be developed within the next 10 to 15 years, we find that a thousand or more interceptors would be needed for a system having the lowest possible mass and providing a realistic decision time. Even so, the total mass that would have to be orbited would require at least a five- to tenfold increase over current U.S. space-launch rates, making such a system impractical.

The Airborne Laser's Performance. A laser weapon now in development has also been proposed for boost-phase defense. The Airborne Laser is being developed to disable short- or medium-range ballistic missiles by illuminating them with a powerful laser beam from distances of several hundred kilometers, heating them sufficiently to cause the structure of the missiles to fail. In principle, this weapon could also disable long-range missiles during their boost phase. Because the laser beam could reach an ICBM within a fraction of a second, its speed is not an issue. However, the range of the Airborne Laser is limited by the distance its beam can propagate through the atmosphere and remain focused. Assuming that it works as planned, its useful range would be about 600 kilometers against a typical liquid-propellant ICBM. This range would be sufficient to defend the United States against such ICBMs launched from North Korea but insufficient to defend against such missiles launched from Iran, unless the laser could be stationed over the Caspian Sea or Turkmenistan. Because solid-propellant ICBMs are more heat-resistant, the Airborne Laser's ground range against them would be only about 300 kilometers, too short to defend against solid-propellant ICBMs from either Iran or North Korea.

Countermeasures. While boost-phase intercept would not be susceptible to some of the countermeasures to midcourse intercept that have been proposed, there is no reason to think it would not face any countermeasures. Effective countermeasures to boost-phase intercept by interceptor rockets could include launching several ICBMs at nearly the same time or deploying rocket-propelled decoys and jammers. Furthermore, ICBMs could be programmed to fly evasive maneuvers that might overwhelm the agility and guidance and control capabilities of the interceptor or exhaust its propellant. Shortening the boost phase would also be an effective countermeasure: it would be practically impossible for any interceptor rocket to reach an ICBM with a boost phase of 2 minutes or less, even if it were launched from a very small country. Countermeasures against the Airborne Laser could include applying ablative coatings or rotating the ICBM to reduce the amount of heat the missile absorbs, launching multiple missiles to overwhelm the Airborne Laser's capabilities, or attacking the aircraft carrying the laser.

Defending the United States

We considered the effectiveness of boost-phase intercept for defending the United States against ICBMs from the two specific countries of concern, North Korea and Iran. The results summarized here for these countries are based on a series of optimistic assumptions. In particular, we have made optimistic assumptions about the missile detection and tracking capabilities available to the defense. Also, we have not fully taken into account the many uncertainties likely to be present in any real engagement, such as uncertainties about the performance of the attacking missile and its trajectory, ignorance of the missile's target, and the unpredictable natural variations in any missile's flight. Nor have we accounted for possible operational delays in processing and transmitting information. All of these factors would make boost-phase intercept more difficult.

We found that terrestrial-based interceptors that burn out in 40 to 50 seconds and reach speeds of at least 6.5 to 10 km/s would generally be required to defend against ICBMs launched from North Korea or Iran. As noted above, such interceptors would have to be substantially larger and capable of higher performance than any that have yet been built or deployed. In a few situations, a 5-km/s interceptor would work against slow-burning liquid-propellant ICBMs. The time available would be significantly greater for very slowly burning liquid-propellant ICBMs having burn times of 5 minutes or longer, but a defense that would work only against missiles as slow as the slowest-burning missiles ever built would risk being ineffective.

North Korea. Defense of all 50 states against typical liquid-propellant ICBMs launched from North Korea would require interceptors with speeds of 6.5 km/s (almost as fast as ICBMs) based in Russia or the Sea of Japan and fired within about 40 seconds of obtaining a firing solution. The intercept locations for most ICBM trajectories from North Korea would be over China, hundreds of kilometers inside its border. Such interceptors would have ranges as long as ICBMs. Consequently, firing them toward China to intercept a North Korean missile could be mistaken for an attack on China, Russia, or other countries. The Airborne Laser might provide an alternative defense against liquid-propellant ICBMs.

To defend against typical solid-propellant ICBMs and provide more than a few seconds of decision time would require interceptors that could reach speeds of about 10 km/s, 50 percent faster than a typical ICBM, in one-quarter of the time it would take an ICBM to reach its maximum speed. The interceptors would have to be based in Russia or the Sea of Japan and fired within 30 to 40 seconds after a firing solution was obtained. Such interceptors could be mistaken for offensive weapons.

Iran. To defend the entire United States against liquid-propellant ICBMs launched from Iran using interceptors based in conventional locations would require basing 10-km/s interceptors in the Persian Gulf, and even this deployment would provide only about 15 seconds of decision time. More decision time would be possible only if interceptors could be based in unconventional locations, such as Turkmenistan or the land-locked Caspian Sea. A system with 6.5-km/s interceptors based in either of these locations could provide a decision time of about 30 seconds.

Defense of the entire United States against solid-propellant ICBMs launched from Iran appears impractical; even a system with 10-km/s interceptors based both in the Caspian Sea and in Turkmenistan or Afghanistan would provide less than 10 seconds of decision time, which is unlikely to be adequate for an operational system.

Defending Only a Portion of the United States. We also considered the feasibility of defending only the contiguous 48 states or only the largest U.S. cities against ICBMs launched from North Korea or Iran. In most cases, this would be no easier than defending all 50 states. If, however, a boost-phase defense were not solely responsible for intercepting all missiles from these countries, the required system performance would be less demanding. Interceptors could hit liquid- or solid-propellant missiles launched from these countries toward some U.S. targets. Such a system could provide a partial defense; for instance, for one U.S. coast but not the other. Coupled with an effective midcourse system, a partially effective boost-phase defense could improve protection of some targets by hitting missiles before they deploy decoys that could overwhelm the midcourse layer. This possibility, however, depends on the midcourse system's being able to handle the unpredictable debris generated by a boost-phase intercept while engaging the warheads, which most likely would survive the intercept. Such a capability would be difficult to achieve.

Defending Against Short- or Medium-Range Missiles Launched from Offshore. Missiles that could be used for a sea-based attack probably are already available to nations of concern to the United States. The Aegis radar system is adequate for tracking such missiles provided it is within a few tens of kilometers of the missile launch location, and a missile similar to the Navy's Standard Missile 2 is adequate for such an engagement without significant modification.

Findings

The Study Group analyzed boost-phase defense against liquid-propellant ICBMs, which the United States may face initially, and against solid-propellant ICBMs, which the nation may face later. The basic parameters of systems that could counter these threats in a variety of geographical situations were identified. In the course of analyzing these systems, the Study Group identified many significant limitations to boost-phase intercept, especially when confronting solid-propellant ICBMs. However, it made no judgment as to whether any or all of these limitations would rule out deployment of such systems on operational, political, or economic grounds. The analysis in the main body of this report supports the following findings. A number (or letter) in parentheses indicates the relevant chapter (or appendix), section, or subsection of the supporting material.

1. **Intercepting missiles during their boost phase presents major challenges not faced by midcourse-intercept systems.**

    - Midcourse systems have 20 to 25 minutes to observe and intercept threatening warheads (A.2); boost-phase intercept systems could have 4 minutes or less to detect, track, and intercept potentially threatening missiles (4.4, 5.4–5.6, 10.4, 15).
    - In midcourse flight, the trajectory of a warhead is ballistic and highly predictable (B); in powered flight, the trajectory of a missile is inherently unpredictable. This unpredictability results from uncertainty about the intended target, the effects of the missile's maneuvers to manage its energy, shape its trajectory, or evade intercept, and its unpredictable thrust variations (4, 12.4, 15.2).

2. **The effective ranges of boost-phase hit-to-kill interceptors, whether land-, sea-, air-, or space-based, are limited by the short duration of ICBM boost phases and practical limits on interceptor fly-out velocities. The range of the Airborne Laser is limited primarily by the distance its beam can propagate through the atmosphere while remaining focused, and to a lesser extent on its power.**

    These limitations have the following consequences:

    - In a hit-to-kill boost-phase defense, the time remaining after an interceptor is fired is so short—less than 170 seconds for a liquid-propellant threat missile and less than 120 seconds for a solid-propellant threat missile—that the defense could fire only once, either a single interceptor or a salvo of interceptors fired virtually simultaneously. There would be no opportunity to recover from a misfire or failure of an intercept attempt (5.4–5.6).
    - Boost-phase defense with interceptor rockets would be possible only if the rockets could be positioned close to the intended intercept point. The intercept point is

typically 400 to 500 kilometers from the missile launch point. The interceptors typically must travel at least 500 kilometers from the interceptor base to reach the intercept point (5.4–5.6).

- Terrestrial-based boost-phase defense—both by interceptors and airborne lasers—also depends on the size of the country that launches the missile, the direction of the missile's flight, and access to areas adjacent to that country, determined by local physical and political geography (5).
- Boost-phase defense using terrestrial-based interceptors could not defend the United States against accidental or unauthorized launches of ICBMs from the interiors of large countries such as Russia or China (5).

3. **The large and unpredictable variations of ICBM boost-phase trajectories and the short time available for engaging them drive the requirements for any boost-phase kinetic kill interceptor.**

Factors contributing to uncertainties in the intercept point include:

- Random and systematic errors in the defense detection and tracking system's measurement of position and velocity and estimate of acceleration of the attacking missile (10.1.4, 12.3.1).
- Lack of knowledge of the missile's target (15.2).
- Normal or induced thrust-time variations of the threat booster (15.2).
- Intentional trajectory shaping, including lofting or depressing the trajectory and maneuvering to manage energy (15.2).
- Intentional evasive maneuvers, such as dog-legs or other maneuvers (12.4).
- Lack of knowledge of the potential type or characteristics of the threat (3.3).
- Uncertainties in the method and times at which the missiles' warheads or submunitions would be deployed (15.2, A.2.2).

These uncertainties reduce the time available for the engagement and require kill-vehicle maneuver velocity and acceleration substantially greater than is generally recognized. These effects are discussed in Chapters 5 and 12.

4. **The only way a boost-phase defense can assure that lethal warheads will not strike a defended area is to disable the attacking missile before the earliest time it can achieve the velocity needed to carry its munitions to that area, because the defense does not know the particular target. This time is uncertain because the missile may fly various trajectories and execute a variety of maneuvers to manage its energy or evade the defense (4.1, 5.1.3, 5.2.1, A.2).**

5. **A robust boost-phase defense against ICBMs would require modern space-based sensors to detect launches and provide initial tracking information needed to launch interceptors. Even so, it would take at least 45 to 65 seconds to detect the launch of an ICBM and establish a track of its trajectory accurate enough to launch an interceptor. Such sensors would also be needed to provide continually updated tracking information to the interceptors as they fly to the target. A system such as the high-altitude Space-Based Infrared System (SBIRS-High) now under development**

could perform these functions if the boost-phase defense requirement is included in its design (10.4).

- While radars with sufficient sensitivity exist, geographic constraints and horizon limitations would require a modern space-based missile warning and tracking system, such as the planned SBIRS-High system, for the earliest detection and initial tracking (10.4). The existing Defense Support Program (DSP) system could provide launch detection and initial tracking, but it would take 30 seconds longer to obtain a firing solution than a system such as SBIRS-High (10.4). Consequently DSP would be useful only against slow missiles, and only if the fastest interceptors were used (5.9.2).
- Additional time margin would be required to allow for the decision to fire and any other intentional or system delays. We use the term "decision time" to encompass any time required beyond the zero decision time case (5.1.3).

6. **While boost-phase defense against slow-burning liquid-propellant ICBMs not employing countermeasures appears technically feasible for some geographic scenarios, the much shorter burn times typical of solid-propellant ICBMs using even 40-year-old technology call into question the fundamental feasibility of any boost-phase intercept of such threats at useful ranges—no matter where or how the interceptors are based—even with the most optimistic assumptions about detection and track times (5.3, 6.11, 8.6).**

   - While liquid-propellant ICBMs typically have powered flight times of 4 minutes or more, solid-propellant missiles typically have three boost stages that burn a total of 3 minutes or less (3.4). This difference is crucial.
   - No matter where or how they are based, interceptors would typically have to travel 500 kilometers or more, requiring prohibitively high flyout velocities (in excess of orbital velocity) and very high accelerations to reach solid-propellant missiles before they have achieved the velocity required to deliver their payloads to the United States (5.3–5.6).
   - By comparison, against liquid-propellant ICBMs, small two-stage terrestrial-based interceptors having modest burnout velocities of only about 5 km/s, such as the largest-sized interceptor that could meet the constraints of the Aegis cruiser vertical launchers or deployment by bombers, could marginally engage threats at about 500 kilometers (5.3). Interceptors having velocities similar to those of ICBMs would provide greater decision time and range for this case but still could not engage solid-propellant ICBMs.

7. **According to U.S. intelligence estimates, North Korea and Iran could develop or acquire solid-propellant ICBMs within the next 10 to 15 years (3.3). Boost-phase defenses not able to defend against solid-propellant ICBMs risk being obsolete when deployed.**

8. **The time constraints imposed on any boost-phase defense system by the short duration of ICBM boost phases would pose significant real-time decision issues.**

   - In most situations, interceptors would have to be fired within a few seconds after confirmation of the launch of a large rocket to intercept it in time to defend the

United States (5.3). The decision to fire interceptors would have to be almost automatic (5.3–5.6).

- Because of the potentially similar flight profiles of ICBMs and space launchers, in many cases the defense system would have difficulty distinguishing a space launch from an ICBM attack. In these cases, the defense would have to shoot at every rocket, unless it had been identified as non-threatening before it was launched (10.4).

9. Despite the variations and uncertainties inherent in the boost-phase trajectories of ICBMs, our analysis indicates that a kill vehicle incorporating current sensor and guidance technology could home on ICBMs in powered flight with a precision compatible with direct hit-to-kill requirements, assuming the kill vehicle's booster could place it on a trajectory that would take it within homing range of the ICBM. The kill vehicle would also have to meet certain critical performance requirements.

Critical kill-vehicle performance requirements include:

- Capacity to shift from guiding on the rocket's exhaust plume to guiding on the rocket body. The Study Group believes this requirement in particular requires more investigation (10.4).
- Ability to acquire and track the rocket body within the plume at ranges of at least 200 kilometers and with sufficient precision, using sensors on board the kill vehicle (12.3).
- Sufficient kill-vehicle acceleration (7–8 g initially and 15 g in the end game), velocity for maneuvering (2 km/s for terrestrial-based and 2.5 km/s for space-based kill vehicles), and guidance system response (0.1 second or less) (12.5).

These requirements would result in kill vehicles with masses substantially greater than is generally appreciated. In our judgment, kill vehicles using technology that would be available in the next few years would have masses on the order of 90 kilograms to 140 kilograms: 90 kilograms for the total divert velocities of 2 km/s that would be required for most ground- and air-based interceptors and roughly 140 kilograms for 2.5-km/s divert velocities that would be appropriate for space-based interceptors and the fastest ground-based interceptors (14.4).

10. Although a successful intercept would prevent munitions from reaching their target, live nuclear, chemical, or biological munitions could fall on populated areas short of the target, in the United States or other countries. This problem of shortfall is inherent in boost-phase missile defense.

- Warheads and submunitions are loosely coupled to the final stage of the ICBM and cannot be assumed to be destroyed by an intercept that destroys or disables the ICBM booster, as borne out by numerous destruct events during flight tests (13.1).
- After an intercept, the munitions and debris will continue on a ballistic trajectory, albeit one that is shorter than intended by the attacker (5.8).
- The warheads or munitions and debris of an intercepted missile will not fall on the country that launched it (5.8).

- Preventing warheads or submunitions and debris of intercepted missiles from hitting the territory of U.S. friends and allies would sometimes require the defense to intercept missiles within a time window as small as 5 to 10 seconds, greatly complicating the already daunting intercept management problem (5.8.1).
- Given the unpredictable variations in trajectories and thrust that characterize ICBMs in powered flight, it is not clear that the intercept can be timed to occur within the narrow window required (5.8.2).

The problem of controlling shortfall could be avoided if the boost-phase defense system could destroy the missile's warheads or submunitions during boost, rather than simply disabling the booster. This is a much more difficult task, and it has not been established that it can be accomplished (13).

11. **Airborne interceptors offer some unique advantages for boost-phase defense, but they also have significant limitations in defending against ICBMs. They could be deployed more quickly than land- or sea-based interceptors in response to new threats, but several backup aircraft equipped with interceptors, as well as refueling aircraft and defensive air cover, would be required for every airborne-interceptor aircraft on station (16.5.3).**

    - An interceptor of any given size has a slightly greater range if launched from a high-altitude platform, because it uses less energy to overcome gravity and aerodynamic drag as it flies out toward its target. However, the constraints on the size and weight of missiles that an aircraft can carry limit the flyout velocity of high-acceleration airborne interceptors to about 5 km/s (16.5.3).
    - Because of their limited flyout velocity, airborne interceptors could engage ICBMs only in situations comparable to the situations in which a 5 km/s surface-based interceptor could engage them. Consequently, using airborne interceptors to defend the United States against long-burning liquid-propellant ICBMs would be possible only if the required intercept locations are within about 500 kilometers of the interceptor-carrying aircraft (5.3.2, 5.5.1).

12. **A constellation of space-based interceptors (SBIs) could, in principle, overcome the geographic limitations of terrestrial-based interceptors and intercept ICBMs launched from much of the Earth's surface. However, they would be subject to range and time constraints similar to those that constrain terrestrial-based systems. Consequently achieving reasonable coverage between the latitudes of 45 degrees North and South would come at a very high cost.**

    - Because a satellite in low-Earth orbit spends so little time over a single spot on Earth, a system having the minimum mass-in-orbit and providing a realistic time to construct a firing solution would require a thousand or more interceptors to intercept even a single liquid-propellant ICBM 5 seconds before it burns out 6.6.[1]

[1]Interceptors in low-Earth orbits revolve around Earth at high speeds while the Earth rotates beneath them. As a result, at any instant almost all the interceptors in a space-based system would be too far away to engage a rocket from any particular launch site. A constellation of a thousand or more interceptors would therefore be required to ensure that at least one would always be within range of a hostile launch.

- The SBI kill vehicles would be similar to those of terrestrial-based interceptors. Because of the high closing velocities of SBI engagements, space-based kill vehicles would require divert velocities of about 2.5 km/s (14.1). Such a kill vehicle would have a mass of roughly 140 kilograms (6.11, 14.4). We estimate that an interceptor that combined the kill vehicle with a two-stage booster to impart the required flyout velocity of 4 km/s in 30 to 40 seconds would have a mass, including its on-orbit support systems, of about 1200 kilograms (6.11).
- To intercept a solid-propellant ICBM launched from North Korea or Iran 5 seconds before burnout, at least 1600 interceptors would be required for a system having the lowest possible on-orbit mass and providing an optimistically short time to construct a firing solution (6.11). Such a system would have a mass in orbit of at least 2000 tonnes. To deploy it would require at least a five- to ten-fold increase in the current annual U.S. launch capacity.
- In practice, more interceptors and mass would be required in orbit because solid-propellant ICBMs launched from North Korea or Iran would usually have to be intercepted before 5 seconds prior to their burnout. The number of interceptors would also increase if the system were designed to assure that two interceptors could be fired against each ICBM, provide more decision time, or have the capability to defend against ICBMs launched nearly simultaneously from closely spaced launch sites (6.6, 6.11).
- Defending against a liquid-propellant ICBM would cut the number of interceptors required to about 700, with a corresponding reduction in the mass of the system, because such missiles burn much longer (15.2.1). However, a system designed to counter only liquid-propellant ICBMs could become obsolete quickly, given the time that would be required to develop and deploy an SBI system (Finding 15), the incentives it would create for emerging missile states to build or procure solid-propellant missiles, and the rate at which solid-propellant technology is proliferating (3.4.2).

13. **Although boost-phase missile defense systems using hit-to-kill interceptors could avoid some of the countermeasures to midcourse intercept that have been proposed, there are effective countermeasures to such boost-phase systems. Many of them have been demonstrated in past U.S. programs for other purposes (5, 9, 12, 15).**

    - Shortening the boost phase of ICBMs. Switching from liquid-propellant to typical solid-propellant ICBMs would cut the boost phase by a minute or more (Finding 6). Boost phases as short as 130 seconds are certainly possible; such missiles would be practically impossible to intercept (5.1.1).
    - Maneuvering the ICBM (15.2).
    - Fractionating the payload during final-stage boost (9.1.2, 9.1.5).
    - Deploying small, rocket-propelled decoys from the missile designed to mask or mimic the radar and electro-optical characteristics of the booster (9.1.3).
    - Launching multiple missiles within a short time. Launching tactical ballistic missiles before launching ICBMs could exhaust the defense's supply of interceptors (9.1.6).

14. **The Airborne Laser (ABL) has been designed to intercept theater ballistic missiles and is scheduled to achieve initial operational capability in about 10 years. It could**

offer some capability for intercepting ICBMs, but would have less range than large ground-based hit-to-kill interceptors. ABL aircraft could be rapidly deployed, but several ABL aircraft, as well as tanker support aircraft and defensive air cover, would be required to maintain one ABL aircraft continuously on station. While the ABL has some self-defense capability, without supporting tactical air cover ABL aircraft would be vulnerable to attack by enemy aircraft or surface-to-air missiles.

- Performance requirements for the ABL are driven largely by the construction materials of the missile and the distance to the target missile—engagement time and uncertainty about the target's trajectory are not issues (21).
- The laser fluence needed to disable ICBMs is currently rather uncertain, making it difficult to estimate accurately the ABL's range if used against ICBMs. The ABL's range is expected to be roughly similar to that of the modest-sized interceptors that could be carried by aircraft (21.5). If so, it could engage only long-burning liquid-propellant ICBMs launched from geographically small, accessible countries (8.3–8.5).
- Defense would be possible using the ABL only if it can be stationed within 600 kilometers of the intercept point of a liquid-propellant missile or within 300 kilometers of the intercept point of a solid-propellant missile. The ABL's laser beam would have to heat an ICBM for several seconds to disable it; hence ABL engagements would have to be timed to avoid the brief periods during which one stage burns out and is discarded as the next ignites (8.7).
- The ABL would have substantial ability to defend the U.S. against liquid-propellant ICBMs launched from North Korea; however, it would have no utility in defending the U.S. against these missiles launched from geographically large, less-vulnerable countries such as Iran. Because of the greater heat resistance of solid-propellant missiles, the ABL could not defend against these missiles launched from either North Korea or Iran. (8.3–8.5).
- The ABL could not disable nuclear warheads or biological or chemical submunitions that have been hardened to survive re-entry at ICBM speeds (20.1).

15. Few of the components that would be required for early deployment (i.e., within 5 years) of a boost-phase defense currently exist. Moreover, we see no means for deploying an effective boost-phase defense against ICBMs within 10 years. Several key components are lacking and are unlikely to be developed in much less than a decade.

- Large, high-acceleration interceptors (5, 16) having the physical characteristics and performance that would be needed for a surface-based boost-phase intercept system have never been built. To counter short- or medium-range missiles launched from platforms off U.S. coasts a missile similar to the U.S. Navy's Standard Missile 2 could be used (5.7.1). We know of no other booster in existence or under development that offers any utility for boost-phase intercept of ICBMs.
- No kill vehicle currently under development has the acceleration and maneuverability required for ICBM boost-phase intercept (11.6, 12.5).

- While radars with sufficient sensitivity exist, such as the THAAD ground-based radar and the Aegis AN/SPY-1 radar, their horizon limitations and geographical constraints would require space-based infrared sensors for detection and initial tracking of threatening missiles (10.2). If SBIRS-High were available and had sufficient capability, it could perform this function (10.4); however, recent reports indicate that SBIRS-High is unlikely to be deployed before 2010 (10.1.2).
- The ABL is currently not expected to be ready for deployment against theater ballistic missiles before 2012 (18.3). Testing and evaluation of the ABL against ICBMs probably would not occur until after it has been tested for its intended mission, intercepting theater ballistic missiles.
- Given the U.S. space launch capability and the high cost of putting mass in orbit, space-based intercept is not practical because small, lightweight sensors, interceptors, and kill vehicles are not currently available (6.11).

16. **Much of the public discussion of missile defense has focused on ICBM attacks, but the threat posed by existing short- or medium-range tactical ballistic missiles launched from ships or other platforms positioned off U.S. coasts is more immediate. It appears that a missile similar to the existing U.S. Navy Aegis Standard Missile 2 could engage short- or medium-range ballistic missiles launched from sea platforms without significant modification, provided that the Aegis ship is within a few tens of kilometers of the launch platform (5.7.1).**

    - According to the U.S. intelligence community, launching short- or medium-range ballistic missiles from platforms a few hundred kilometers off U.S. coasts would be much less demanding technologically than launching ICBMs. The missiles that would be needed for such an attack are already available (A.1).
    - Many of the challenges that make ICBM defense difficult—such as geographic constraints that prevent the defense from positioning interceptors close to the missile's boost trajectory, delays in detecting and tracking the target missile, uncertainties about the exact target, and the problem of controlling shortfall—are absent when the threatening missile is launched from a ship near the United States.
    - The Airborne Laser might also be able to counter this threat, but the Study Group did not analyze this possibility.

17. **In our view, there are many issues for a boost-phase intercept system that require further study before the true capabilities and deployment timelines of boost-phase missile defense can be determined.**

    These issues include:

    - The communications, command, and control networks and systems that would be required for a boost-phase intercept system to function with the reliability required under the extreme time pressures that a defense system would face, particularly one using space-based interceptors.
    - The capability for transferring the interceptor's guidance from tracking the missile's luminous plume to tracking the missile itself ("plume-to-hardbody handover") (10.4). This task is technically challenging and not well understood. More realistic

modeling, testing, and evaluation would be required to demonstrate that it can be done reliably under all engagement conditions.

- The effects on liquid- and solid-propellant boosters of a body-to-body collision with a kill vehicle need more extensive modeling and realistic testing (13).
- The realistic capabilities that would be needed to deploy, maintain, and control a space-based system must be understood before an informed decision can be made about the feasibility of such a concept. Given the extreme sensitivity of system costs to changes in the mass of space-based interceptors, a careful assessment of the effects of countermeasures should be included (6).
- The lethality of the ABL when used against ICBMs, especially solid-propellant ICBMs. Further modeling and realistic testing are needed under the wide range of conditions that would be encountered in intercepting ICBMs during their boost phase (20).

Concluding remarks

In assessing the feasibility of boost-phase missile defense using hit-to-kill interceptors or the ABL, we attempted to make optimistic assumptions to bound the performance of such systems. In some cases we made assumptions that appear technically possible but may not be realistic on other grounds. An important example is the assumption in some of our analyses that interceptors could be fired as soon as a target track has been constructed, without allowing additional time for decision or assessment. In other cases we simply examined the performance that would be required to make the system workable, without making any judgment about whether such components could realistically be deployed. An example of this kind is our consideration of an interceptor having a flyout velocity 40 percent higher than an ICBM's velocity. We emphasize that the choices made in this study were used to obtain upper bounds on performance; their use does not imply that the Study Group endorses these choices as realistic in all cases.

Given the results that follow from our assumptions, we conclude that while the boost phase technologies we studied are potentially capable of defending the United States against liquid-propellant ICBMs at certain ranges of interest, at least in the absence of countermeasures, when all factors are considered none of the boost-phase defense concepts studied would be viable for the foreseeable future to defend the nation against even first-generation solid-propellant ICBMs (5, 6.11, 8.6).

Chapter 1

Introduction to the Report

Contents

1.1 Boost-Phase Intercept

Boost-phase intercept systems for defending the United States against ballistic missile attack are the focus of increasing public discussion,[1] and Department of Defense spending on such systems is growing, with the prospect of much larger expenditures in the future.[2] Boost-phase weapons would seek to destroy attacking missiles while their boosters are still burning and before they have released nuclear, chemical, or biological munitions. The technical aspects and feasibility of such weapons are the subject of this report.

For more than four decades, the United States has invested substantial resources in developing anti-ballistic missile systems.[3] During most of this period, the focus of the effort was on developing weapons and systems that could defend against the thousands of intercontinental ballistic missiles (ICBMs) fielded by the Soviet Union. In response to the end of the Cold War and other changes in the international situation, the emphasis of

[1]See for example Richard L. Garwin, Hearing of the Senate Foreign Relations Committee, May 4, 1999; John Deutch, Harold Brown, and John P. White, "National Missile Defense: Is There Another Way?", *Foreign Policy*, Summer 2000; President George W. Bush, speech at the National Defense University, Washington, D.C., May 1, 2001; Robert Wall, "Growing Interest Bolsters BPI", *Aviation Week & Space Technology*, August 13, 2001; Geoffrey Forden, "Laser Defenses: What if They Work?", *Bulletin of the Atomic Scientists*, v. 58, 48–53, 2002.

[2]About $600 million was spent on boost-phase intercept technologies in FY02; an additional expenditure of $7.4 billion on boost-phase research and development is planned over the next 5 years. See Department of Defense FY2003 Budget Estimate, RDT&E, Defense Wide, Vol. 2, Missile Defense Agency, February 2002.

[3]See Stephen Daggett and Robert D. Shuey, "National Missile Defense: Status of the Debate", Congressional Research Service Report for Congress, 97-862 F, updated May 29, 1998.

the U.S. program to defend against long-range missiles shifted first to systems that could counter accidental or unauthorized launches of a few ballistic missiles against the United States and, more recently, to systems that could counter missiles that might be deployed by countries that have missile development programs and with which the nation does not currently have friendly relations.

The U.S. intelligence community has identified several countries of concern that are developing long-range missiles.[4] Although the intelligence community judges that U.S. territory is currently more likely to be attacked by nuclear, chemical, and biological weapons delivered by means other than missiles, it is the assessment of most of the intelligence community that the United States is likely to face ICBM threats from some of the countries of concern during the next 15 years.[4] The growing sale and transfer of ballistic-missile-related technologies, materials, and expertise has generated concern that some unfriendly countries might be able to deploy full-range ICBMs, including solid-propellant ICBMs, with little warning.[5] The U.S. intelligence community has judged that several countries of concern are technically capable of developing within the next decade the ability to launch short- or medium-range ballistic missiles against coastal regions of the United States from ships or other platforms positioned hundreds of kilometers offshore.[6] To counter these potential threats, the United States is actively pursuing a variety of missile defense options.

The principal focus of the nation's current national missile defense program is on weapons that would destroy warheads after they have been launched by ICBMs but before they re-enter the atmosphere.[7] During this so-called midcourse phase of flight, which lasts approximately 25 minutes, warheads follow predictable ballistic trajectories outside Earth's atmosphere. Using ground-based interceptors located at only a few sites, a midcourse intercept system potentially could defend the United States from missiles launched from almost anywhere on Earth.

Midcourse-intercept systems, however, must contend with two challenges. A single missile could launch multiple warheads or even dozens of chemical or biological submunitions, thereby overwhelming the defense. In addition, many argue that the system could be defeated by countermeasures and penetration aids, including large numbers of lightweight

[4]National Intelligence Council, *Foreign Missile Developments and the Ballistic Missile Threat to the United States Through 2015, unclassified summary of a National Intelligence Estimate*, December 2001, available at: http://www.cia.gov/nic/pubs/. Robert Walpole, Testimony by the National Intelligence Officer for Strategic and Nuclear Programs before the International Security, Proliferation, and Federal Services Subcommittee of the Governmental Affairs Committee, U.S. Senate, February 11, 2002, available at http://govt-aff.senate.gov/031102witness.htm.

[5]Donald Rumsfeld et. al., *Executive Summary of the Report of the Commission to Assess the Ballistic Missile Threat to the United States*, July, 1998; Robert H. Schmucker, "Engineering and Proliferation Analysis of Third World Theatre to Intermediate Range Ballistic Missiles", contribution to Year 2000 Multinational BMD Conference, Philadelphia, PA, 5–8 June, 2000 (unpublished).

[6]National Intelligence Council, *Foreign Missile Developments and the Ballistic Missile Threat to the United States Through 2015, unclassified summary of a National Intelligence Estimate*, September 1999, available at: http://www.cia.gov/nic/pubs/. National Intelligence Council, *Foreign Missile Developments and the Ballistic Missile Threat to the United States Through 2015, unclassified summary of a National Intelligence Estimate*, December 2001, available at: http://www.cia.gov/nic/pubs/. Robert D. Walpole, "The ballistic missile threat to the United States," speech by the National Intelligence Officer for Strategic and Nuclear Programs at the Carnegie Endowment for International Peace, 17 September 1998, available at http://www.cia.gov/cia/public_affairs/speeches/1998/walpole_speech_091798.html.

[7]We use the phrase "national missile defense" to indicate a defense system intended to defend the national territory of the United States rather than, for example, U.S. allies or troops based outside the United States, because it describes the goal of such a defense concisely. We note, however, that the present administration no longer uses this terminology.

decoys that would be difficult to discern from real warheads outside the atmosphere.[8]

The difficulty of meeting these challenges has led to growing advocacy of boost-phase intercept as a possible alternative.[9] Boost-phase systems potentially offer three important advantages: the possibility of destroying missiles before they can deploy multiple warheads or submunitions, the presumed difficulty of developing countermeasures, and the ease of tracking the bright exhaust plumes of ICBMs in powered flight. A boost-phase defense that used surface- or air-based interceptors or the Airborne Laser (ABL) would also be attractive, some argue, because their limited ranges would not threaten Russian or Chinese land-based nuclear missile forces. Space-based boost-phase weapons have also been proposed as the first layer in a layered defense system.[10]

The boost phase of an ICBM typically lasts no more than 3 or 4 minutes. Consequently, even fast interceptor missiles would have to be fired from bases close to anticipated ICBM intercept points.[11] Therefore, surface- and air-based interceptors would be capable of countering only those missiles launched from countries that are sufficiently small geographically, and on boost-phase flight paths that are within range of interceptors stationed in international waters or in neighboring countries willing to host them. The Airborne Laser is similarly constrained because of its own engagement range limitations.

1.2 The American Physical Society Call for the Study

In spite of the government's growing interest in boost-phase intercept systems and the resources being committed to developing them, little quantitative information on the technical feasibility, required performance, and potential advantages and disadvantages of such systems is available to the public. To increase public understanding of these matters, the American Physical Society convened a study group of physicists and engineers, including individuals with expertise in sensors, missiles, rocket interceptors, guidance and control, high-powered lasers, and missile-defense-related systems, to assess the technical feasibility of boost-phase intercept systems.

Many of the key questions concerning the technical feasibility and required performance of boost-phase intercept systems can be answered by considering basic physics and engineering principles. The American Physical Society therefore asked the Study Group to produce an unclassified report based on publicly available information. The intention was to provide the membership of the Society, other scientists and engineers, policy makers, and the public with basic information about the science and technology of boost-phase intercept systems. The American Physical Society hopes that this report, which describes the technologies and technical requirements of these systems, their advantages and limitations,

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[8]George N. Lewis and Theodore A. Postol, "Future Challenges to Ballistic Missile Defense", *IEEE Spectrum*, September 1997, p. 60; Andrew Sessler et al., *Countermeasures: A Technical Evaluation of the Operational Effectiveness of the Planned U.S. National Missile Defense System*, Union of Concerned Scientists/MIT Security Studies Program, April 2000; for a contrary view, see William A. Davis, "Why Missile Defense Will Work", *Inside Missile Defense*, October 3, 2001, p. 10.

[9]Richard L. Garwin, "Boost-Phase Intercept: A Better Alternative", *Arms Control Today*, September 2000, p. 8; Theodore A. Postol, "Boost-Phase Missile Defense Concepts for Protecting the U.S. from Postulated Rogue-State ICBMs, 2001, unpublished; Hans Mark, "A White Paper on Defense Against Ballistic Missiles", *The Bridge*, Vol. 31, No. 2, Summer 2001, p. 17.

[10]Jeffrey A. Isaacson, "There's a Better Way to Missile Defense", Los Angeles Times, May 3, 2001, p. A13; Donald Rumsfeld, Memorandum on Missile Defense Program Direction, January 2, 2002; James Dao, "Plan to Stop Missile Threat Could Cost $238 Billion", New York Times, February 1, 2002.

[11]George R. Pitman, "Boost-Phase Intercept Missile Defense: A Critical Analysis", 2001, unpublished.

and the technological challenges in developing and deploying them, will help in evaluating proposals to build such systems.

1.3 Scope of the Study

The Study Group was asked to consider primarily boost-phase intercept systems that could defend the United States from attack by ballistic missiles of intercontinental range. In particular, the Study Group was asked to evaluate the potential of systems using terrestrial-based or space-based hit-to-kill rocket interceptors, or the ABL, for this purpose. Space-based laser systems were not considered because the technology that would be required for such systems is at a much earlier stage of development. We also considered briefly the feasibility of defending against attacks by ship-based ballistic missiles launched off U.S. coasts using short-range interceptor rockets. The Study focused on technology that could, in principle, begin to be deployed in about 10 years.

1.4 Issues Not Addressed

A number of important technical issues were identified but not analyzed in detail, either because the necessary information was not available to us or because they lay outside the scope of the Study. These include the feasibility of building and deploying long-range, high-acceleration interceptors; the beam quality and certain other performance characteristics of the ABL; the effectiveness of kinetic-energy weapons or laser beams in disabling boosters, warheads, and submunitions; communications, command, control and battle management; survivability; and system complexity. Nor did the Study consider nuclear-tipped interceptors for boost-phase defense, or midcourse or terminal intercept systems.

Finally, the Study did not consider policy issues, such as the economic, arms control, strategic stability, or foreign policy implications of developing, testing, or deploying boost-phase intercept weapons.[12]

1.5 The Varieties of Boost-Phase Intercept Systems

The Study examined systems that would use interceptor missiles based either on land, on ships at sea, on aircraft, or on satellites in space. Small interceptors could be carried by satellites in low-Earth orbits. Somewhat larger interceptors could be carried by large aircraft or bombers. Still larger interceptors could be based on ships or on land. The range of an interceptor is limited by the highest speed that is technically feasible and the time available to complete the intercept. Systems that utilize surface- or air-based interceptors could potentially defend against missiles launched from limited geographical areas. In contrast, a space-based system could in principle defend against missiles launched from anywhere on Earth. However, due to Earth's rotation and the motions of orbiting satellites, a system of

[12] For discussions of the latter issues, see for example Dean Wilkening, *Ballistic Missile Defense and Strategic Stability*, Adelphi Paper No. 334, International Institute for Strategic Studies, London, 2000, p. 59; William J. Perry, San Jose Mercury News, September 10, 2000; *Pugwash Workshop on Nuclear Stability and Missile Defense*, Pugwash Occasional Papers, Vol. 2, No. 2, March 2001; Camille Grand, "Ballistic Missile Threats, Missile Defenses, Deterrence, and Strategic Stability", Mark Smith, "Missile Proliferation, Missile Defenses, and Arms Control", and James Clay Moltz, "Forecasting the Strategic-Military Implications of NMD Deployment" in *International Perspectives on Missile Proliferation and Defenses*, Occasional Paper No. 5, Center for Nonproliferation Studies, Monterey Institute of International Studies, March 2001.

thousands of satellites armed with interceptors would be required to defend against missiles launched from a single launch site.

The Study also considered the Airborne Laser, which was originally planned as a weapon for theater missile defense but is now also being considered for national missile defense. It uses a high-powered chemical laser beam. Mirrors direct the beam toward the target missile. The beam travels at the speed of light and would therefore reach the target in a fraction of a second. Such a beam could potentially disable a missile in powered flight by heating its body long enough (at least several seconds) to cause structural failure. The effectiveness of the ABL against ICBMs would depend on the power and quality of its beam and the degree to which the beam could be focused on the target in the presence of the atmospheric turbulence at the altitudes at which it would operate.

1.6 Requirements for Success

In a boost-phase intercept, the largest and most fragile targets are the ICBM's boost stages. Moreover, a boost stage that is burning produces a bright exhaust plume that is easily spotted by sensors in orbit or on the interceptor, although the interceptor must eventually home on the body of the booster and not its plume. If a burning boost stage were hit by an interceptor, it would quickly lose thrust, but the collision would not necessarily disable all the missile's munitions, and the missile (perhaps in fragments) and its munitions would not fall straight down. Instead, they would continue on ballistic trajectories, falling to Earth short of the intended target. Consequently, to ensure that a missile's munitions do not strike the United States, a boost-phase defense must disable the missile before it has reached a speed sufficient to carry its munitions to the United States. Later interception may be too late, because the munitions may have already separated from the missile. The system would then have to contend with the problems of a midcourse intercept.

Unless the boost-phase intercept system is able to destroy the missile's munitions, they will strike somewhere outside the boundaries of the country that launched the missile. Consequently, an intercept could cause live nuclear warheads or biological or chemical munitions to fall on populated areas of the United States or other countries. This risk is inherent in boost-phase defense.

1.7 Challenges

The greatest challenge for a boost-phase defense system is the very short time within which the intercept must be completed. The boost-phase of a liquid-propellant ICBM typically lasts about 4 minutes.[13] The shorter duration of the boost phases of solid-propellant ICBMs—typically about 3 minutes—is even more daunting. The narrow time window dominates every aspect of boost-phase intercept, driving the required performance of the detection and tracking systems, the interceptors, and the kill vehicle. About 1 minute is required to confirm the launch of a potentially threatening rocket, leaving slightly less than 3 minutes to decide whether it is an attacking ICBM and if so, to fire an interceptor and disable or destroy the ICBM. The interceptor must give its kill vehicle a velocity that will carry it sufficiently close to the expected intercept point, and the kill vehicle must then be able to home on the missile and maneuver to collide with it. The missile would be destroyed or disabled by the kinetic energy of the collision. (The kinetic energy released in

[13]Five-minute burn time missiles are also considered, though these are regarded as a less likely threat.

the collision of an interceptor with an ICBM is greater than the chemical energy that could be released by explosives carried by the interceptor.)

While it delivers energy at the speed of light and is therefore not constrained by flyout time, the ABL has engagement range limitations caused by atmospheric effects and the durability of the target. The challenges are to preserve the focus of the high-energy beam on the target after propagation through the atmosphere and to maintain the beam on the target long enough to disable the missile. The time required varies greatly depending on the structural material used in the target missile.

1.8 A Guide to the Report

The remainder of this first volume contains Part A of the Report. Part A provides an overview of boost-phase missile defense and compares it with other approaches to missile defense in the context of the anticipated threat. It first describes the analytical approach and key assumptions made in our analysis of boost-phase intercept systems that would use terrestrial-based or space-based interceptor rockets employing the kinetic energy of a collision to disable or destroy the target missile. It then describes the analytical approach and key assumptions made in our analysis of potential utility of the Airborne Laser for boost-phase intercept of ICBMs. Part A analyzes the performance each of these three types of systems would require to defend the United States against missiles launched from three geographical locales and ends with a discussion of possible countermeasures to these approaches to boost-phase missile defense.

Chapters 2 and 3 frame the boost-phase defense problem in relation to alternative approaches to missile defense and describe the rationale for the missile models used in the Study. Chapters 4 and 5 analyze the basic requirements for engaging a missile in time to defend the United States and then examine the relationship between target missile characteristics, interceptor performance, and allowable basing areas for surface-based interceptors. Chapter 4 describes the engagement assumptions and analytical methods we adopted and develops the approach we used to simulate engagements. Chapter 5 uses these results to determine where the different interceptors would have to be based to defend the United States against ICBMs launched from North Korea, Iran, or Iraq.[14] This chapter also discusses whether it is possible to avoid causing possibly live munitions to strike other countries.

In Chapter 6, the methods developed and some of the previous results are applied to analyze the feasibility of a global missile defense system employing space-based boost-phase interceptors. Here, the methodology previously used in analyzing terrestrial-based intercept systems is applied to analyze the required performance and size of a system of space-based interceptors intended to defend the United States against ICBMs. This analysis shows how the total mass that must be launched into orbit depends on the number and size of interceptors required for coverage, which in turn depends on the burn time of the attacking missiles, the flyout capability of the interceptors, and the mass of the kill vehicle.

In these analyses, we assumed that if the kill vehicle could reach the target missile in time, the intercept attempt would succeed, deferring to Part B of the Report the question of the capabilities the kill vehicle would require to home on the interceptor and hit it, and resulting size and mass of the kill vehicle. This "best case" approach allowed us to

[14] As explained in the Executive Summary, although Iraq is not considered likely to pose an ICBM threat to the United States in the foreseeable future, the Study Group has retained the analysis of defense against ICBMs from Iraq to illustrate the requirements for defending against a country that is intermediate in size between North Korea and Iraq.

determine the minimum requirements for intercepting different types of missiles and to establish the tracking geometric and measurement uncertainties and geographic constraints on engagements, including possible interceptor basing locations for specific scenarios.

Chapter 7 introduces the methodology for analyzing boost-phase engagements of liquid- and solid-propellant ICBMs by the ABL. The performance parameters and their relationship to the engagement are discussed. Chapter 8 analyzes the missile-defense capabilities of the ABL in actual geographical scenarios comparable with the approach used for surface-based intercepts in Chapter 5.

Part A concludes with Chapter 9, a discussion of countermeasures to boost-phase intercept likely to be encountered by kinetic-kill intercept systems and the ABL.

Glossaries of acronyms and technical terms are provided at the end of this volume.

Volume II contains Parts B through D of the Report. Part B addresses what it would take for a kinetic-kill boost-phase defense—regardless of its basing mode—to acquire, track, hit, and destroy a target missile. Chapters 10 through 14 summarize the sensor and kill-vehicle flyout and homing performance that would be required for terrestrial- and space-based interceptors to have a high probability of hitting an ICBM during its boost phase. Chapter 10 analyzes the potential performance of missile acquisition and tracking sensors. We estimated the uncertainties in determining the trajectory of an attacking ICBM caused by tracking system limitations and variations in the trajectory of the ICBM—both intended and unintended—when the kill vehicle relies on data from off-board and on-board sensors to maneuver to hit the target. We then analyzed the kill-vehicle performance—including divert velocity, acceleration, and guidance-and-control system response time—that would be required to hit a maneuvering ICBM. The issues associated with confidently disabling an ICBM are examined in Chapter 13. Based on these results, we were able to estimate the mass of a kill vehicle with the required performance. The mass of the kill vehicle ultimately determines the total mass of any hit-to-kill interceptor system.

In Part C, we describe our modeling of illustrative threat missiles in Chapter 15 and interceptors to defend against them in Chapter 16. These models were used in the analyses presented throughout the Report.

Part D of the Report explores the physics and technology requirements for successfully utilizing the ABL to disable ICBMs during their boost phase. The analysis of the ABL described there relies on some of the assumptions and portions of the analysis in Part A. Part D analyzes propagation of high-power laser beams through the atmosphere, laser-targeting issues, and the effective range of the ABL when used against various types of ICBMs, assuming that the planned performance of the ABL is achieved. An overview to the analysis of the ABL for boost-phase defense is presented in Chapter 17. Chapter 18 describes the operation of the laser itself, and Chapter 19 discusses the propagation of the laser beam through the atmosphere. The factors involved in disabling a missile using the ABL are described in Chapter 20, and ABL engagements are discussed in Chapter 21. Deployment issues are described in Chapters 22.

Appendices provide supporting information on the categories and characteristics of ballistic missiles, how the missile and interceptor trajectories used in the Study were computed, the tracking of missiles during boost-phase engagements, and the propagation of the ABL's beam through the atmosphere. For convenience, the glossaries of acronyms and technical terms are repeated at the end of Volume II.