

# Boost-Phase Defense Against Intercontinental Ballistic Missiles

**An American Physical Society study concludes that disabling ICBMs before they release their munitions would be very difficult at best and, in some cases, impractical.**

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For more than four decades, the US has devoted substantial resources to developing antiballistic-missile systems.<sup>1</sup> During most of that period, effort was focused on developing systems that would defend against the thousands of intercontinental ballistic missiles (ICBMs) fielded by the Soviet Union. Recently, attention has shifted to systems that could counter ICBMs that North Korea or Iran might deploy. Although neither country currently has ICBMs, the US intelligence community projects that they are likely to develop or acquire them within 10 to 15 years.<sup>2</sup>

To counter that potential threat, the US is pursuing several missile-defense options.<sup>3</sup> Currently, the primary focus is on a system that would destroy warheads after they have separated from their ICBM boosters but before they reenter the atmosphere. This so-called midcourse phase of flight typically lasts 25–35 minutes.

A midcourse-intercept system would have to overcome two main challenges. First, a single ICBM could release several nuclear warheads, or dozens of chemical or biological “bomblets,” overwhelming the defense. Second, many experts argue that a midcourse-intercept system could be defeated by countermeasures such as lightweight decoys that would be difficult to distinguish, outside the atmosphere, from real warheads.<sup>4</sup> The difficulty of meeting those challenges has led some to argue that a boost-phase intercept system would be a better alternative,<sup>5</sup> or at least a valuable complement, to a midcourse-intercept system.<sup>6</sup>

A boost-phase intercept system would seek to disable attacking missiles while their boosters are still burning. Such a system could take advantage of the ease with which the bright exhaust plumes of ICBMs can be tracked, and it could prevent ICBMs from releasing their munitions or decoys if it could disable them early enough in the boost phase.

## The APS study

In the fall of 2000, the American Physical Society appointed an advisory committee, chaired by one of us (Lamb), to consider whether APS could play a useful role in helping the nation make the best possible choices concerning missile defense. The committee noted that, although the idea of boost-phase intercept systems was attracting growing attention, little information about their technical requirements or potential advantages and limitations was available to the public. Boost-phase intercept systems, the committee pointed out, are still at the conceptual stage, and many key questions about them could

be answered by considering basic physics and engineering principles. Concluding that an unclassified, impartial, and authoritative study of the basic scientific and technical issues involved in boost-phase missile defense would be useful, the advisory committee recommended that APS undertake such a study.<sup>7</sup>

In response to that recommendation, the APS convened a study group of physicists and engineers, in July 2001, to assess the science and technology of boost-phase intercept systems and produce a report that would help scientists, engineers, policymakers, and the public to evaluate proposals for building such systems. The study group included experts on sensors, missiles, interceptors, guidance and control, high-power lasers, and missile-defense related systems. The membership of the group, which included the three of us, is listed in box 1. The group was assisted by several dozen outside technical consultants drawn from the defense community.

The study group was initially asked to focus on “hit-to-kill” systems that would use land- or sea-based interceptor rockets to strike and disable ICBMs. But subsequently, because of changes in the US missile-defense program and the policy context, the scope of the study was expanded to include systems that would use air- or space-based interceptors or the Airborne Laser (ABL) system to disable ICBMs. The Airborne Laser was originally designed to disable shorter-range (“theater”) ballistic missiles by heating the attacking missile until its structure fails. Now that system is also being considered for use against ICBMs. We did not consider space-based laser weapons, because the requisite technology is not expected to be ready for at least 15 years.

Our group considered a range of possible defense goals, including defending all 50 states, only the contiguous 48 states, the largest US cities, only one coast, or just Hawaii. Among our generally optimistic assumptions about the potential performance of boost-phase defense systems were that the attacker would have only early-1960s missile technology, whereas the defense would have access to any technology that could begin to be deployed 10 years from now. In assessing the technical feasibility of boost-phase intercept, we did not consider issues of battle management, communications, command, control, reliability, or potential countermeasures, any of which could make the defense’s job more difficult.

The study group’s report was released to the public in July 2003. It is available online,<sup>8</sup> and is being published as a supplement to *Reviews of Modern Physics* (see PHYSICS TODAY, September 2003, page 26).

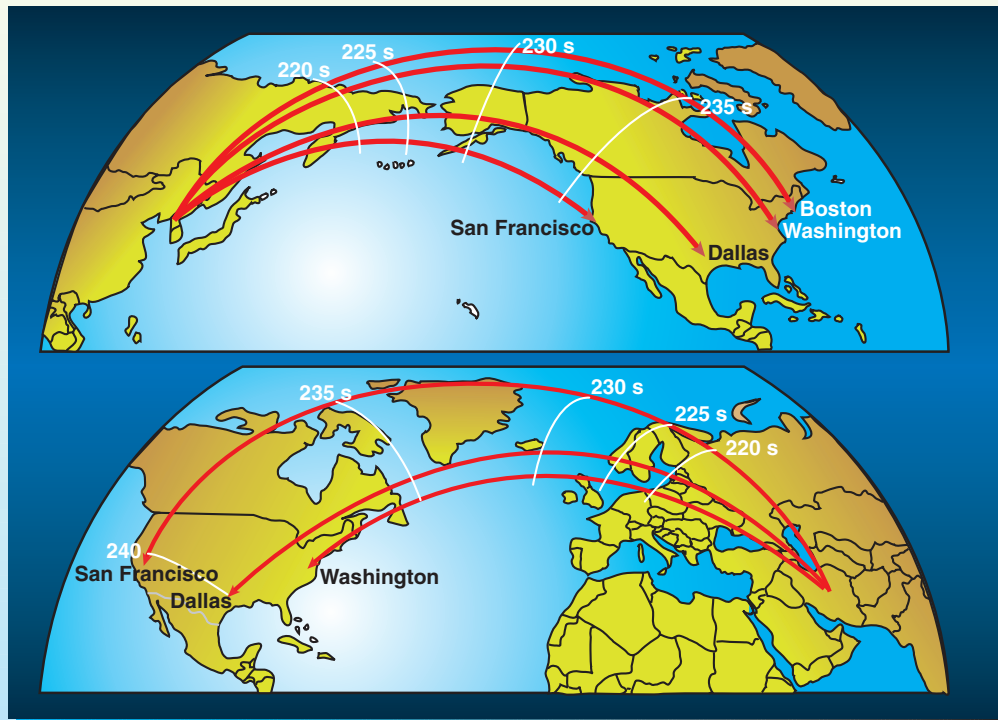
## Using interceptor rockets

The feasibility of boost-phase defense using interceptor rockets hinges on the answers to two crucial questions: Can interceptors reach the attacking ICBM in time? If so, can their “kill vehicles” (the separated final stages) home in on and hit the missile?

The answer to the first question depends on the performance of the ICBM, the location of the attacking country relative to the US, the availability of interceptor bas-

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**Figure 1. Intercontinental ballistic missile trajectories** from North Korea (top) and Iran (bottom) to various targets in the contiguous 48 states. These ground tracks span an azimuthal range of about  $40^\circ$  at each missile launch site. Time-labeled white contour lines that cross the red ground tracks show where the munitions payload of a liquid-propellant ICBM with a range of about 12 000 km and a maximum burn time of 240 s would strike if the missile's thrust were terminated by interception at the indicated time after launch. Even at these latest times, the missile would still be within 500 km of its launch site. To defend Alaska against a missile from North Korea, for example, a boost-phase defense would have to disable it no later than 227 s after launched. Its warheads, however, might then strike Russia.



ing sites near the ICBM's flight path, the performance of the missile warning and tracking system, and the acceleration and final velocity of the interceptor. The answer to the second question depends on the capabilities of the ICBM and the interceptor's kill vehicle. To address these questions quantitatively, the study group constructed computer models of ICBMs that the system might have to face, missile detection and tracking systems, interceptor rockets, and kill vehicles. We then used the models to simulate engagements of ICBMs by various interceptors.<sup>9</sup>

The time available to intercept an ICBM before it could release its munitions depends strongly on whether it is a liquid-propellant or a solid-propellant missile (see box 2). Neither North Korea nor Iran currently has ICBMs. We therefore developed computer models of ICBMs that those countries might field, based on historical patterns and the unclassified summaries of recent National Intelligence Estimates.<sup>2</sup> The study focused on three model missiles: a liquid-propellant ICBM with a maximum burn time of 240 s and two solid-propellant ICBMs, both with burn times of 170 s but with different acceleration profiles. These ICBMs have nominal maximum ranges of 12 000 km, enough to reach all of the US from North Korea and most of it from Iran.

The maximum flight time the interceptors have available depends on how early they can be fired and how late they can disable the missile and still protect the US. Global geography determines the possible flight paths of ICBMs and how early they must be intercepted, whereas regional geography determines how close to the flight paths interceptors could be based. Geographic factors dictate that US interceptors must be based far from the intercept point. Therefore they would have to intercept ICBMs at or near the last possible moment.

A key time in boost-phase defense is the earliest time, after the launch of a threatening rocket (which could be a missile or a peaceful space launch), that interceptors can be fired against it. To fire interceptors, the defense must detect a signal, identify it as coming from a large rocket, and track the rocket long enough to determine its approx-

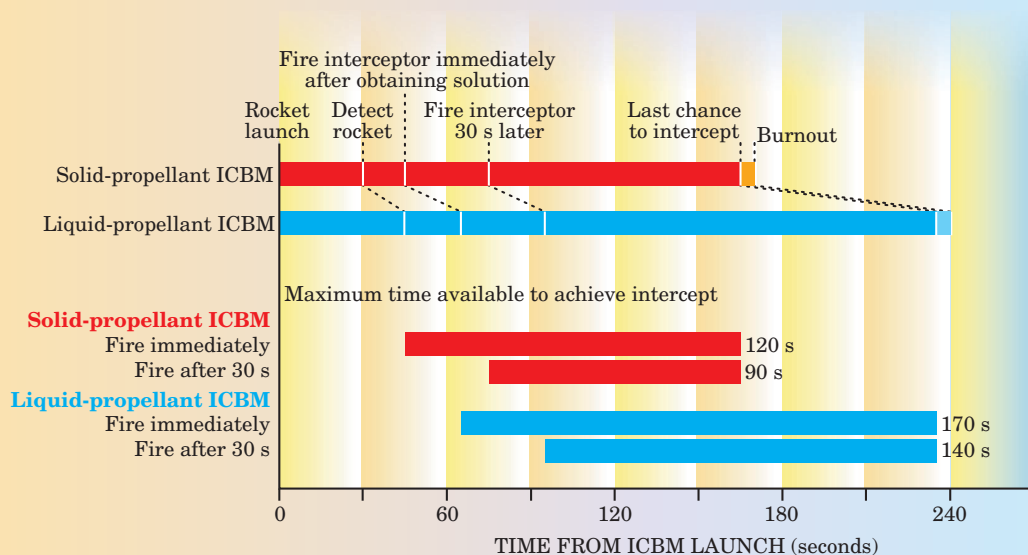
imate heading, so that the defense knows in what general direction to fire its interceptors.

The current US space-based system for detecting and tracking missiles is the so-called Defense Support Program (DSP) system, which uses infrared sensors on satellites in geosynchronous orbits. Each satellite has a telescope that continually scans the whole disk of Earth, looking for IR radiation from the hot exhaust plumes of rockets. To reduce clutter, DSP telescopes deliberately operate at wavelengths at which they cannot see the exhaust plume of a rocket until it has reached an altitude of 10 km. Then they sample the plume signal only once every 10 s. The DSP satellites are inadequate to support a boost-phase defense system.

Satellites of the new Space-Based Infrared System-High (SBIRS-High) are scheduled to begin replacing DSP satellites within 10 years. To explore what might be possible with a modern space-based infrared system, we considered the capabilities of a system that would use the most advanced sensors currently available in the laboratory to see down to the ground and scan at a rate of 1 Hz. Even these state-of-the-art sensors would not detect a rocket until it has risen above any dense clouds. But at mid-latitudes, dense clouds are relatively rare above 7 km. So we assumed that a modern system would first see a bright spot when a missile reaches that altitude.

However, jet aircraft or bright fires on the ground can also produce spots. The signature of a missile is a bright spot that has a high horizontal velocity. By simulating data from a notional modern space-based IR system and constructing missile tracks for our model ICBMs, the study group found that interceptors could be fired as early as 65 s after the launch of the liquid-propellant ICBM model, if no time is allowed for contingencies or making decisions. For the faster-burning solid-propellant ICBM models, the earliest possible firing time would be 45 s.

A second key time in boost-phase defense is the latest time the kill vehicle can intercept a particular ICBM and still protect the defended area. As explained in box 2, a successful intercept is unlikely to disable ICBM's warheads or munitions. They will be deflected only slightly, if at all, and



**Figure 2. Timelines** for intercepting an ICBM launched from North Korea or Iran, assuming either that interceptors are fired as soon as the general heading of a threatening rocket is determined by a modern space-based detection and tracking system or, alternatively, after assessing the threat for 30 more seconds. The last safe intercept time for these trajectories is taken to be 5 s before the missile would burn out. To prevent the ICBM from striking populated areas short of the target (see figure 1), it would, in many cases, have to be intercepted even earlier.

will continue on ballistic trajectories. Consequently, the defense is assured of success only if the interceptor hits the attacking missile before the missile has given its warheads or munitions a velocity that will cause them to strike the area to be defended. The latest safe intercept time depends on the offensive missile, its target, and its programmed trajectory. If the capabilities of the missile and its flight path are known exactly, that time can be determined by using plots like figure 1, which shows the ground tracks of ICBM trajectories from North Korea and Iran to various points in the US. But because those details will never be known in advance by the defense, the time and place where an ICBM must be intercepted will be uncertain. We ignored that uncertainty in our analysis.

The two key times—the earliest time that interceptors could be fired against a particular ICBM and the latest intercept time that would spare the defended target—can be used to construct engagement timelines like those shown in figure 2. Such timelines, which also ignore uncertainty, emphasize how little time a boost-phase defense would have to stop an ICBM.

### Interceptors and kill vehicles

An interceptor is a two- or three-stage booster rocket whose payload is a rocket-propelled kill vehicle. The booster hurls the kill vehicle toward the point where it is expected to intercept the target missile—typically 400 km to 500 km downrange from the missile's launch site. The booster must place the kill vehicle on a trajectory that will take it close enough to the target that it can maneuver to hit the target

before the last safe intercept time. To achieve that goal, the booster must rapidly accelerate the kill vehicle to a speed high enough to reach the missile, which was launched 45 to 95 s before the interceptor was fired.

The study group constructed computer models of a half-dozen different interceptors but focused on the three shown in figure 3, which span the capabilities of interest. All three would be new missiles that would have to be developed and tested. The Minuteman III ICBM is included in the figure for comparison with the interceptors. The least capable, I-2, would fit in the vertical launch system currently aboard the US Navy's Aegis ships. The most capable interceptor, I-5, accelerates five times faster than the Minuteman III to a final velocity almost 50% greater than the Minuteman's. The I-5 is, in fact, longer than the Minuteman III and twice as massive. Our study used the I-5 to illustrate the capabilities of a system using a surface-based interceptor with a performance at the limit of what might be practical. We assumed that interceptors would receive nearly continuous in-flight updates on their position, velocity, and acceleration, and those of their quarry, from off-board tracking systems.

Once the interceptor's booster has burned out, it deploys its kill vehicle. Above about 70 km, dynamic pressure and frictional heating are low enough that the kill vehicle can open its sensor windows. By that time, the ICBM is accelerating rapidly and may change course unpredictably due to random thrust variations or purposeful targeting or evasive maneuvers. The kill vehicle must therefore be highly maneuverable, with sensors, a sophisticated guidance and control system, and thrusters to enable it to track the target and maneuver to hit it.

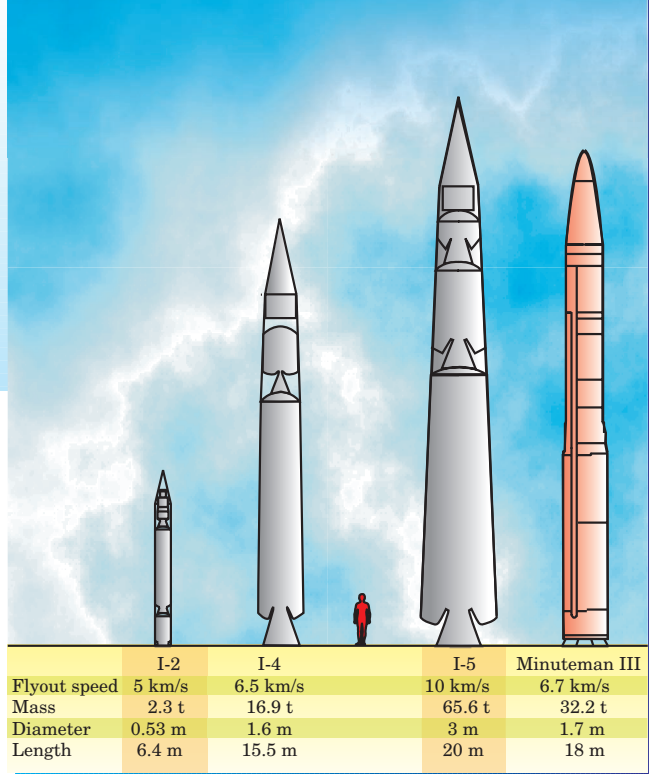
Figure 4 illustrates a few of the possible trajectories that an ICBM might follow during its boost phase. The azimuths of possible trajectories from North Korea or Iran to targets in the 48 states span about 40°. The boost-phase defense would have to be prepared to intercept an ICBM anywhere within a volume more than 100 km on a side, over a range of intercept times that could be uncertain by up to 70 s.

When the kill vehicle is still far from its quarry, it can use IR sensors to home in on the ICBM's exhaust plume. But as the kill vehicle gets closer, it must shift to homing in on the missile's body, which is much smaller and cooler than the exhaust plume. Detecting the missile's body near or through the bright exhaust plume is very challenging, even with a suite of multiwavelength sensors. The study group judged

### Box 1. Members of the APS Study Group

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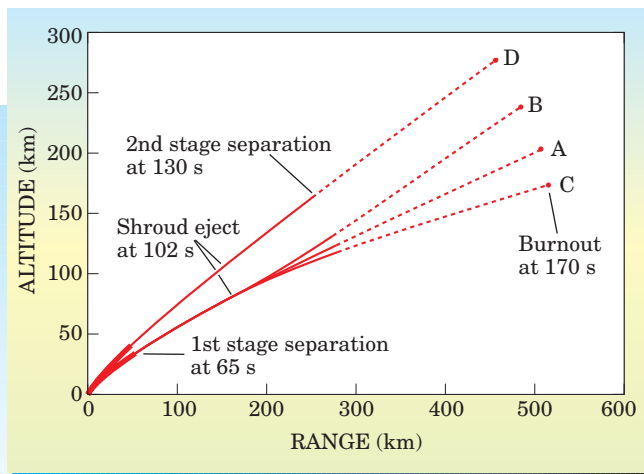
**Figure 3. Three interceptor types** modeled in the APS boost-phase defense study, with a Minuteman III ICBM shown for comparison. The interceptor I-2 would fit into launchers aboard some current US naval vessels. The flyout speed for an interceptor is its speed when it releases its kill vehicle on a vertical trajectory. The interceptor I-5 accelerates five times faster than an ICBM to a final velocity almost 50% greater than the ICBM's velocity at the end of its boost phase. The study group constructed the I-5 model to investigate the performance of a system with ground-based interceptor capabilities at the limit of what is practicable.

that a passive IR sensor on the kill vehicle could estimate the location of the ICBM within about 100 m. An appropriate light detection and ranging (LIDAR) system could then image the missile and provide tracking information until the kill vehicle hits or misses its target.

We found that, to hit an ICBM reliably at the expected high closing velocities, the kill vehicle must be able to respond to any change in the missile's trajectory in less than 100 ms. It must be able to accelerate at  $15g$  during the last few seconds before impact, and it must be capable of an integrated velocity change of at least 2 km/s. At the expected closing velocities (10 km/s or higher), a kill vehicle that hits an ICBM booster where it's relatively solid will release a kinetic energy equivalent to a mass of TNT 10 times that of the kill vehicle. So no explosives would be needed.

### Terrestrial-based interceptors

Figure 5 illustrates the type of analysis that underlies the study group's findings for terrestrial-based interceptors. The flight paths from North Korea that would be most difficult to intercept are to the US East Coast, because their boost-phase ground tracks lie farthest inland. The figure shows the basing areas from which 10-km/s interceptors could reach solid-propellant ICBMs early enough in their



boost phase to defend Boston under two different scenarios. If the interceptors are fired as soon as a firing solution is obtained, the basing area is significantly larger than if the situation is assessed for a further 30 s.

By analyzing such maps, the study group judged that using terrestrial-based interceptor rockets to defend the 50 states against liquid-propellant ICBMs launched from North Korea may be feasible, but that would push the limits of what is possible physically, technically, and operationally. Defending all 50 states against liquid-propellant ICBMs from Iran, we concluded, would be much more difficult. Taking all relevant factors into account, including the uncertainties and technical command-and-control issues, we reached the conclusion that defending the 50 states against solid-propellant ICBMs, from either North Korea or Iran, would not be feasible.

### Space-based interceptors

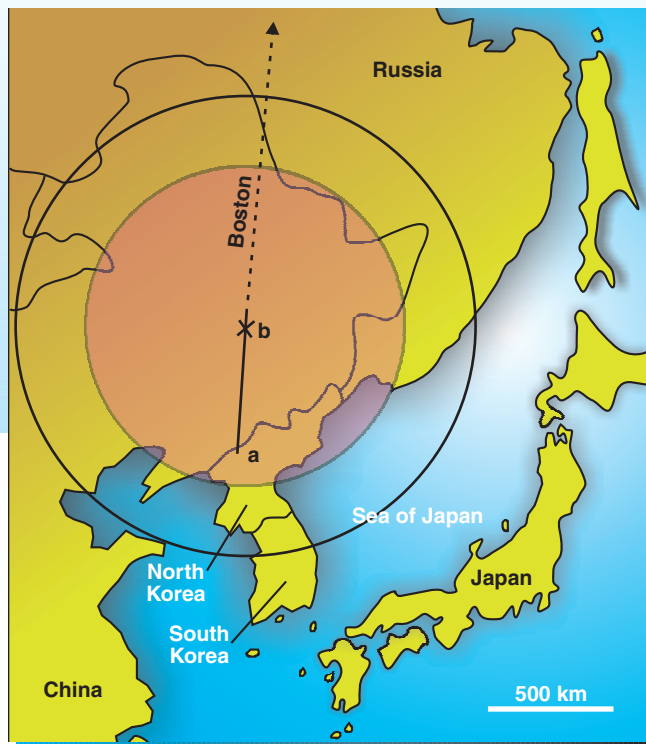
A system of hit-to-kill interceptors based on satellites in low-Earth orbits could, in principle, defend against ICBMs launched from anywhere on Earth. Many of the considerations for such a system are the same as for a system of terrestrial-based interceptors. The last safe time to intercept is the same no matter where the interceptor is based, and the interceptor performance required to home in on the missile is the same. However, the distance a space-based interceptor must travel is dictated not by geography but by the distance of the satellite from the missile's flight path. And that depends on the number of satellites and their altitudes.

The cost of a space-based system depends sensitively on its total mass. The minimum system mass that will suffice is determined by a series of tradeoffs. Faster interceptors can fly farther in the time available, reducing the number required. But a faster interceptor must be more massive, because it has to carry more propellant and because its kill vehicle requires greater velocity-change capability to cope with the greater closing speeds. For a given terminal velocity, faster-accelerating interceptors can fly farther, but they need more massive motors, greater structural mass, and a kill vehicle with more maneuvering propellant.

Another important factor is the altitude of the

**Figure 4. Illustrative boost-phase trajectories** for a solid-propellant ICBM. The missile's maximum-range trajectory is labeled **A**. But the ICBM could fly out on a spectrum of other trajectories with little reduction in range. In cases **B** and **C**, the missile initially flies its maximum-range trajectory, but after 110 s the flight path angle is increased or decreased by about  $20^\circ$ . Such "doglegs" can also have transverse components that take the trajectory out of its initial plane. Trajectory **D** has been lofted to achieve a higher burnout altitude. In all these cases the range is at least 88% of the maximum. They show that the intercept point could lie anywhere in a volume about 100 km on a side. Adding to the problem of predicting the intercept point is the possibility that the missile is, instead, a slower-accelerating liquid-propellant ICBM.

**Figure 5. Basing areas** from which a 10-km/s interceptor could defend against a solid-propellant ICBM flying from point **a** in North Korea toward Boston. The ICBM must be intercepted before point **b** to prevent its munitions from striking the target. If the interceptor is fired at the earliest possible moment, it can be based anywhere within the outer circle. But if the defense wishes to assess the situation for 30 more seconds before firing, the interceptor must be based within the inner circle. Because these circles incorporate many optimistic assumptions, the study group judged such a defense to be impractical when all factors are considered. The basing areas from which a 6.5-km/s interceptor could defend against a liquid-propellant ICBM are similar. Defense against a liquid-propellant ICBM was judged to be feasible, in principle, but only with interceptors faster than 6.5 km/s.



interceptor satellites. If there were no atmospheric drag, the optimum altitude would be close to the expected altitude of intercepts, typically about 200 km. But at that altitude, atmospheric drag would be significant. Our analysis showed that satellites could be maintained at an altitude of 300 km with little mass penalty by using small, ion-propulsion engines.

In the light of all the tradeoffs, we considered what would be the minimum total mass of a system that met a “baseline” requirement: intercepting a single solid-propellant ICBM launched from North Korea or Iran 5 s before it burns out, with interceptors fired with zero decision time. The kill vehicle would have to be capable of an integrated velocity change of 2.5 km/s.

The results of our analysis are summarized in figure 6. The mass of a kill vehicle capable of meeting the baseline requirements is 136 kg. For such a kill vehicle, the system mass is minimized for interceptors with a full fueled mass of 820 kg. These interceptors could accelerate at about 10 *g* to final velocities of 4 km/s. Roughly 1600 satellites orbiting at an altitude of 300 km would be needed to have at least one, and typically two, in position to inter-

cept an ICBM from North Korea or Iran. The total mass in orbit would be about 2000 tons. Deploying such a system would require a five- to tenfold increase in the current US space-launch capability.

Defending against a single, slow-burning, liquid-propellant ICBM would require only about 700 satellites. But a system that could counter only liquid-propellant ICBMs could quickly become obsolete, especially given the long time needed to deploy it and the incentives it would give adversaries to build or procure solid-propellant missiles.

Our results for space-based systems neglect some of the requirements that are included in our analysis of terrestrial-based systems. When we include those requirements, the number of satellites needed is more than doubled. On the other hand, we estimated that significant advances across a range of technologies might reduce the required mass in orbit, perhaps by as much as 50%.

## Box 2. Challenges of Boost-Phase Intercept

► *The boost phase of an ICBM is brief.* The rocket motors of a liquid-propellant ICBM burn for only 4 or 5 minutes; those of a solid-propellant ICBM burn for only about 3 minutes. Therefore the defense has little time to decide whether to fire interceptors, and interceptors have little time to reach the ICBM before its boost phase ends.

► *Large, high-acceleration, high-speed interceptors are required.* The brevity of the boost phase dictates that the ICBM must be intercepted within 400–1000 km from the interceptor’s basing location. Furthermore, to defeat some attacks, interceptors would have to accelerate 5 times faster than the ICBM and reach speeds up to 50% greater than the ICBM’s.

► *ICBMs in powered flight accelerate unpredictably.* They are typically steered during their boost phase and could also maneuver to evade intercept. Beyond these purposeful movements, the thrust of solid-propellant missiles is inherently somewhat unpredictable. Consequently, the kill vehicle must have a fast guidance and control system, high acceleration, and a substantial capability to change its velocity.

► *Even a successful intercept cannot be expected to disable an ICBM’s munitions.* The munitions are loosely coupled to the missile and hardened to survive re-entry. Therefore, live munitions will continue onward after the interception, and they could strike populated areas of the US or friendly countries short of the target.

## Defense using the Airborne Laser

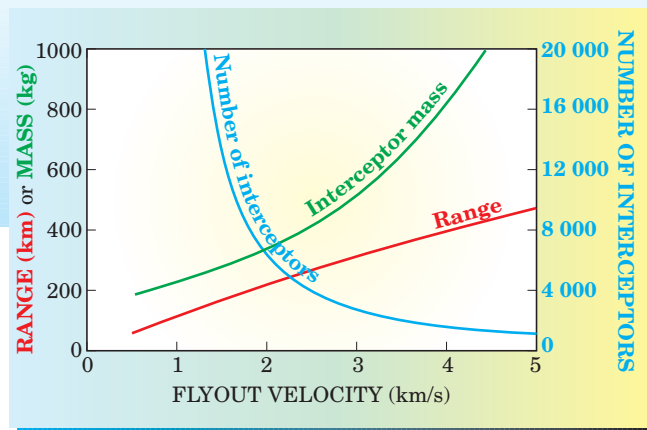
The ABL would disable a missile by using a megawatt laser to heat it until it becomes too weak to withstand the dynamic loads to which it is subjected as it accelerates. The plan is to house the laser in a large airplane with optical and tracking systems for focusing the laser beam on the target and compensating for the atmospheric turbulence that would otherwise defocus it. Because the ABL would deliver its energy at the speed of light, it could attack an ICBM as soon as the missile rises high enough in the atmosphere.

The ABL was initially intended for battlefield use against short- or medium-range missiles. If used to attack ICBMs, the ABL would generally shoot upward, rather than downward, from an aircraft stationed safely outside unfriendly territory. The fluence (energy per unit area) required to disable a missile depends on the missile’s construction. The skin of a liquid-propellant missile is thin and relatively fragile, whereas the shell of a solid-propellant missile is the missile’s combustion chamber, designed to withstand very high temperatures and pressures. Thus one needs about eight times more fluence to disable a solid-propellant ICBM than to disable a liquid-propellant ICBM.

The range of the ABL will depend on the power of the



**Figure 6. A space-based system** of boost-phase interceptors involves many tradeoffs. The range, mass, and required number of interceptors with an acceleration of 10 g are plotted against flyout velocity (the speed at which the interceptor releases its kill vehicle) for a system that meets the baseline requirement discussed in the text. The total mass, and therefore the cost, of the system is minimum when it has 1600 orbiting 820-kg interceptors with flyout velocities of 4 km/s.



laser, its ability to track the target missile and focus the laser on it, and the ability of the adaptive optics to compensate for the defocusing effects of atmospheric turbulence. Turbulence is expected to be less of a problem for attacking ICBMs than for shorter-range missiles, because ICBMs can be engaged at altitudes where the atmosphere is thin. On the other hand, attacking ICBMs from a safe distance requires greater range.

In assessing the usefulness of the ABL, the study group adopted its publicly reported design goals: 3 MW of power focused into a 1.2-m-diameter beam (close to the diffraction limit) that could illuminate the target missile for up to 20 s. We also considered the utility of systems with greater and lesser capabilities. We found that if the ABL achieves its design goals, it would have a range of about 600 km against liquid-propellant ICBMs. That would be useful against liquid-propellant ICBMs launched from North Korea, but not from Iran. Against solid-propellant ICBMs, its range would be only about 300 km, too short to be useful in any of the scenarios we examined. The ABL's range is relatively insensitive to its power.

## Conclusions

The findings of the APS boost-phase study differ from the more optimistic conclusions of some previous studies for a number of reasons. Rather than focusing on particularly vulnerable missile designs, we considered both liquid- and solid-propellant ICBMs with performances typical of missile technology 40 years ago. We did not, for example, assume that the boost phases of attacking missiles would last 300 s or more, as some earlier studies had done. Nor did we assume that the defense would know in advance the initial direction of the ICBM's flight, its target, or the path it would fly to the target. Furthermore, we carefully analyzed the kill-vehicle performance that would be required to intercept an ICBM during its boost phase.

Here are the principal findings of the APS study group on boost-phase intercept systems for national missile defense:<sup>8</sup>

- ▶ Defending the 50 states against liquid-propellant ICBMs from North Korea may be feasible, but would push the limits of what is possible physically, technically, and operationally.
- ▶ Defending the 50 states against liquid-propellant ICBMs from Iran would be much more challenging.
- ▶ Defending the 50 states against solid-propellant ICBMs from North Korea or Iran is unlikely to be practical when all factors are considered.
- ▶ Defending only the West Coast against ICBMs from North Korea would be easier than defending all 50 states.
- ▶ Defending only part of the US against ICBMs from Iran would not be easier than defending all 50 states.
- ▶ A boost-phase defense could contribute to a layered defense, provided the second layer can handle the unpredictable debris generated by the boost-phase layer.
- ▶ Effective countermeasures against boost-phase-intercept missile defense are possible, and they should be taken into account.
- ▶ Defending against shorter-range missiles launched from

hostile ships off US coasts would be feasible with interceptors similar to current Navy missiles, provided that the missile-carrying ships are able to stay within about 40 km of threatening ships.

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9. The study group's methodology is described in detail in chap. 2 of ref. 8. ■