Chapter 7

Ballistic Missile Defense Technologies

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INTRODUCTION

This chapter and chapter 8 describe the technologies applicable to ballistic missile defense and point out some of the uncertainties that further research may hope to resolve. Ballistic missile defense technologies and ballistic missile defense policies, of course, are interdependent. BMD policy choices, the subject of the preceding chapters of this report, are constrained by the state of our technology. At the same time, however, policy decisions influence technological advances by providing (or withholding) resources and incentives to extend our knowledge and capabilities.[1]

Feasibility

The overall feasibility of ballistic missile defense technologies involves a set of related issues which become increasingly harder to answer definitively. Scientific feasibility-whether or not something is physically possible—is obviously necessary for any BMD concept, but it is by no means sufficient. Technical and economic feasibility questions go on to ask whether a device permitted by the laws of nature can actually be built at a reasonable cost within a reasonable amount of time. Assuming that a system can be designed and built according to specifications, operational feasibility issues address the questions of whether it can actually be deployed, tested, maintained, and operated with a high degree of confidence.

Overriding all of these considerations is the issue which forms the crux of the BMD technical debate: any effective BMD system must be "robust," in that it must operate and endure against a reactive adversary intent on defeating *it. The dynamic* competition between offensive and defensive technologies-among measures, countermeasures, and counter-countermeasures—forces the successful development and implementation of BMD technologies to be far more than a purely technological accomplishment, such as reaching the moon or splitting the atomic nucleus. The moon and the nucleus did not hide, run away, or shoot back.

Evaluating the robustness of a prospective defensive system requires making assumptions about the motivations and relative technical skills of the two sides. It also requires a clear conception of the system's intent. Is a successful defense one which can defeat a given threat and deters threat growth? Or is it one which can defeat the threat and provokes growth, forcing the Soviets to spend a lot of money?

Failure to take full account of the offense-defense competition can lead to what has been called the "fallacy of the last move, in which some action is evaluated as if the strategic competition were frozen immediately afterwards. However, although the concept of a "last move" in the competition between offense and defense does not make sense, the starting point of such a competition is well defined. Massive, diverse, and highly effective offensive forces dominate the strategic relationship today. From that starting point, advanced defensive technology and advanced offensive technology will evolve together, in the absence of political agreements to regulate that competition. If both offenses and defenses evolve at comparable rates, the present dominance of the offense will clearly be maintained. Economic questions are as important as technical ones, since the outcome of a technological competition depends in part on who is better able to pay for it. These economic questions are discussed further in chapter 8.

If it turns out that offensive technologies have developed so far along their learning curve that their rate of continued technical progress slows, evolving defensive technolo-

[1]For example, technology in the area of pollution control has primarily been driven by policy decisions.

gies might make progress in eroding the great distance currently existing between the two. The relevant question is whether it is likely that an arms development competition will close that gap. To say that the time is ripe for offense dominance to give way to defense dominance either prejudges the outcome of this technological competition, or assumes that a political agreement will be reached which will ensure that defenses catch **up and overtake offenses.**

Technological Prediction

Even aside from the all-important question of effectiveness against a reactive opponent, predicting future technical feasibility is a difficult business. Experts can have hunches and gut feelings, and they can make elaborate technical calculations. However, firm answers cannot be obtained without experimentation. No one, regardless of technical credentials or creative ability, is an expert when it comes to predicting the future. Secretary of Defense Caspar Weinberger has called attention to Albert Einstein's 1932 observation that "there is not the slightest indication that [nuclear] energy will ever be obtainable."2 Arms Control and Disarmament Agency Director Kenneth Adelman has similarly recalled the warning that Admiral Leahy, President Truman's Chief of Staff, gave the President in 1945: "The [atomic] bomb will never go off, and I speak as an expert in explosives. "3 Adelman warned that technical critics of the Strategic Defense Initiative "may well turn out to be just as shortsighted in retrospect as many of their predecessors have been in hindsight today. "

In the context of the time, however, Einstein was correct. The "indications" that nuclear energy might be obtainable had yet to be discovered. If a major effort to develop nuclear power had been undertaken before basic research had revealed the phenomenon of heavy element fission, it might have focused on the wrong end of the periodic table and floundered for years.

When the "experts" do make mistakes, they err in both directions. Just as breakthroughs have been made which were previously predicted to be impossible, other foretold inevitabilities have never come to pass. For example, General David Sarnoff, Chairman of the Board of the RCA Corp., claimed in 1955 that "[I]t can be taken for granted that before 1980 ships, aircraft, locomotives and even automobiles will be atomically fuelled." John von Neumann, the father of the modern computer and a member of the Atomic Energy Commission stated the following year that "[a] few decades hence, energy may be free-just like the unmetered air."*

One way to attack the question of predicting the feasibility of a given technical accomplishment (setting aside the question of reactive opponent) is to specify a time limit. Is a Boeing 747 airliner feasible today? Of course—it has been in service for more than 15 years.[4] Would it have been feasible in 1940? No–unless 30 years were allotted at that time for its development, including some unanticipated and rather fundamental inventions that made it possible, and provided that large expenditures were allocated for producing and operating its predecessors.

A more relevant measure is to ask whether progress can be accelerated significantly by a crash ("technology-limited' program. Perhaps a 747 could have been developed by 1955 or 1965 if doing so had been a compelling national priority. However, attempting to build one before all of the required technologies had matured to their 1970 levels would probably have produced a very different airplane at much greater expense.

Organization of This Chapter

This chapter introduces the technological components which might contribute to future

'Speech before the Foreign Press Center, Dec. 19, 1984.
Quoted by Ambassador Adelman in "SDI: Setting the Record Straight, " speech before the Baltimore Council on Foreign Affairs, Aug. 7, 1985.

*AI1 quotes in the preceding three paragraphs can be found in *The Experts Speak: The Definitive Compendium of Authoritative Disinformation*, by Christopher Cerf and Victor Navasky, a joint project of *The Nation* magazine and the Institute of Expertology (New York: Pantheon Books, 1984).
'Pan Am introduced the Boeing 747 airliner to commercial service with a flight from New York to London on Jan. 22, 1970.

ballistic missile defense systems. It reviews the characteristics of many of the relevant technologies and outlines the key uncertainties concerning those technologies' potentials. Readers who do not wish to immerse themselves in technological details are invited to concentrate on the sections labeled "Issues," with the descriptions preceding those sections used as reference material. In addition, the following chapter (chapter 8) summarizes some of the major issues of technological feasibility.

This chapter also examines how the technological building blocks need to be put together, and it introduces some of the systems issues relevant to integrating the pieces into a coherent whole. It does not attempt to predict exactly how each of the technologies will evolve, and it compares different contenders for some given task to each other only in a general way.

The chapter was prepared with access to classified materials. For the most part, those classified data concerned schedules, budgets, and technical matters too detailed for this discussion. A few relevant classified details and concepts are discussed in a classified annex.

BMD TECHNOLOGIES

Overview

BMD Concepts

Ballistic missile defense systems as described by the ABM Treaty and as primarily pursued prior to 1980 consisted of ground-based interceptors of various ranges supported by ground-based radars. These systems would attempt to intercept ballistic reentry vehicles (RVs) as they descended toward the United States, either prior to or just after they reentered the Earth's atmosphere. Current BMD concepts posit systems that can intercept ballistic missiles and their RVs at all stages of their flight, from shortly after launch to just prior to detonation.

Layered Defenses

The basic concept is to use layered defenses, which provide the defense with several opportunities to attack the incoming warheads. Early layers would reduce the number of warheads that later layers would have to handle; later layers would "mop up" those that get through the early layers.

It has become convenient to discuss defensive layers which are associated with each phase of a ballistic missile's flight. Since the missile has different properties in each phase, different defensive components are associated with the different phases.

The first opportunity to engage the missile would be in its *boost phase,* when the ICBM's booster motor is burning. A second layer might operate in the *post-boost phase* after the booster has dropped away, leaving a *post-boost vehicle* (PBV or *bus)* which aims the individual warheads at their targets and lets them go. Decoys and other defense penetration aids can also be dispensed by the PBV during this phase. The post-boost is followed by a *midcourse phase* of up to 20 minutes in length during which the RVs and decoys coast towards their *targets; the* last phase is the *terminal or reentry phase,* lasting less than a minute, which starts when the RVs reenter the Earth's atmosphere and the lighter decoys burn up.

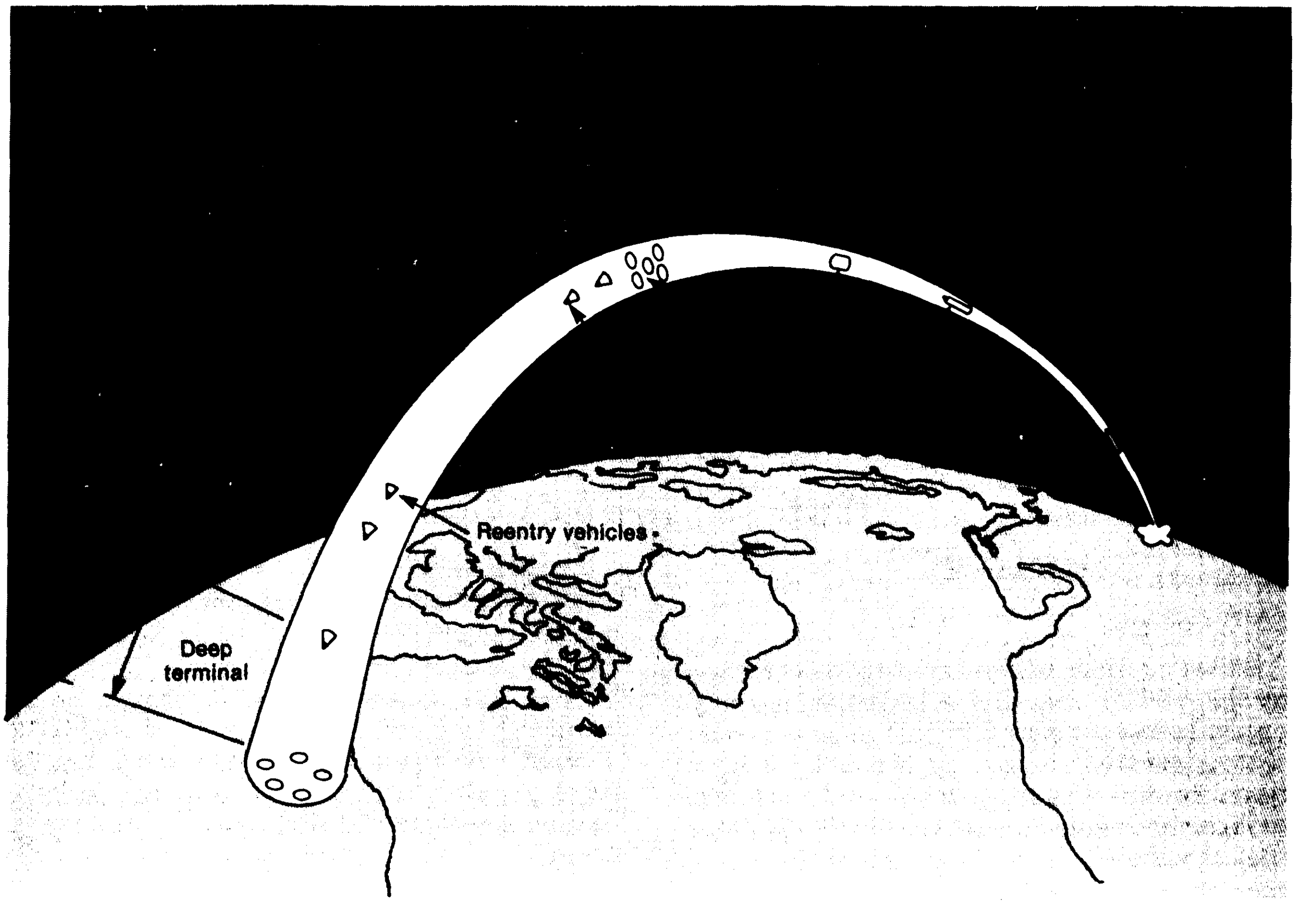
Operation of each layer is controlled by a *battle management* system, which also coordinates between the layers and provides overall supervision and control.

Properties of the Phases

Boost Phase.– During boost phase, the hot gases in the booster's exhaust produce a large, easily detected infrared signal, or *signature,* especially as the rocket rises above the clouds and the denser layers of the atmosphere. For current missiles, the boost phase lasts 3 to 5 minutes.[5] However, not all this period is avail-

[5]See J. C. Fletcher, "The Technologies for Ballistic Missile Defense, " Issues *in Science and Technologu,* fall 1984, p. 15.

Figure 7-1 .—Multilayered Space Defense



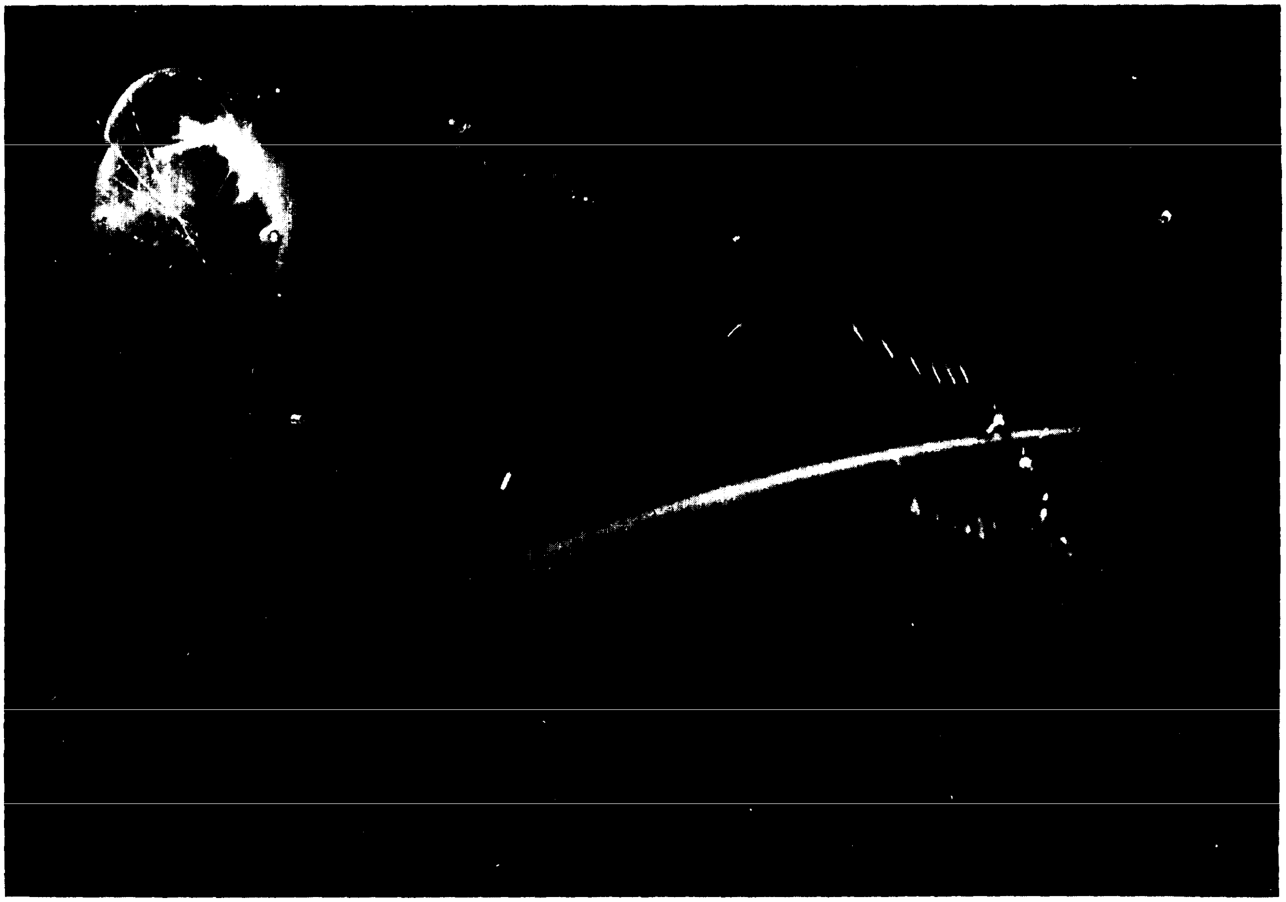
Each of the phases presents specific opportunities to the corresponding defensive layer. The phases are boost, post-boost, midcourse and terminal.

SOURCE U S Department of Defense

able for the defense to attack the boosters. The defensive system must first detect the launch, determine that there is actually an attack in progress, decide to engage the boosters, and allocate defensive weapons platforms to the boosters. How much time this would take depends on how automated the system would be and how quickly decisions could be made. In particular, requiring that human intervention be necessary before the defense can commence firing imposes extreme time constraints on command and control procedures.[6] Possibly, a succession of alert conditions could be established which, under day-today conditions, would require human intervention before boost-phase defenses could engage an attack (leaving surprise attacks to be handled by later layers), but which in times of crisis would permit the defense to engage boosters autonomously if an attack were detected. Such a procedure, of course, would increase the incentive for surprise attack.

Successful engagement in the boost phase can provide a high degree of leverage-i. e., the destruction of one booster results in the destruction of all its RVs and decoys. There is also another sort of leverage involved–the boosters are much more vulnerable than the RVs, providing another advantage to attacking the boost phase.

‘Requiring human decisionmaking could pose even more severe problems in terms of platform self-defense, when only a very short time may be available to characterize and engage attacking weapons before they come within lethal range.



B

One consequence of the high leverage of boost-phase defenses is that small errors in boost-phase BMD performance are magnified to become larger errors in the later phases. Each missile that survives the boost phase may ultimately produce hundreds of objects (RVs and decoys) that must be tracked, discriminated, and attacked by later layers. Because effective discrimination is vital to the success of the midcourse layer, successful midcourse defense maybe tightly linked to the success of the boost phase.

By their nature, boost-phase defenses have little ability to defend *selectively*. While a booster is burning, it may be possible to determine where it came from, wherein general it is headed, and what kind of missile it is. However, until the individual RVs are released by the PBV, their specific targets cannot be determined. Therefore, boost-phase defenses cannot effectively conduct *preferential defense,* in which limited defensive resources are concentrated on defending only some sites at the expense of permitting attacks on others to continue unimpeded. In this manner, a limited defensive capability can be used to save a greater number of sites than would be possible with a random allocation of defenses (see discussion of preferential defense in chapter 5).[7]

Even without the ability to conduct preferential defense, a boost-phase defense which eliminates some fraction of an attack can deny the offense the ability to conduct a highly structured attack which requires warheads to arrive at specified targets in a precise order. Such an attack would be much more difficult to carry out if some fraction of the offensive boosters were intercepted by the boost-phase layer. A structured attack, intended to blind or destroy components of the defensive system, might make it easier to penetrate later defensive layers. Therefore, the inability to conduct such an attack might make those later layers more effective.

Post-Boost Phase.—The post-boost phase may last as long as 6 minutes, but it could be much shorter. As this phase progresses, the PBV dispenses RVs and decoys and therefore loses value as a target. Therefore, leverage is high at the beginning of the post-boost phase and low at the end. Although the individual RVs on each PBV are relatively "hard" (difficult to destroy with certain types of defensive weapons), the PBVs themselves might be ''softer, adding to the leverage of the post-boost phase. However, if a PBV is disabled without disabling the RVs still attached to it, those RVs may still have to be handled by later defensive layers.[8]

The post-boost defense has more time to get ready than the boost-phase defense (since it can get ready during the boost phase), and it may have more total time to engage each individual target. However, targets must be engaged early in the post-boost phase to achieve best results. As in the case of boost-phase defenses, small errors in post-boost performance can have larger consequences in the later phases. Unlike boost phase, however, the performance of the post-boost phase depends on when targets are killed as well as on *how many are* killed. Since targets become less valuable as time goes on, uncertainties in timing will affect overall post-boost-phase performance. Selectivity in the post-boost-phase defense–the ability to conduct preferential defense—is similar to that of the boost phase.

Midcourse Phase.—Most of an RV'S flight time is spent in the midcourse, the period between release from the bus and reentry into the Earth's atmosphere. This period lasts about 20 minutes for ICBM RVs; it may be much shorter for SLBM RVs. Although there is much more time to find and engage targets in the midcourse than in the earlier phases, there is also much more to do. Before a target can be engaged, it must be discriminated from decoys and possibly from debris; imperfect discrimination capability will result in shooting at objects that are not really targets and in withholding fire on objects that should actually be attacked. To kill the 10 RVs carried on one SS-18 in boost-phase, the defense must find and destroy one target in the few minutes that the boost phase lasts. To kill the same number of RVs in midcourse, the defense must sort through possibly hundreds of objects in order to find and destroy the 10 RVs in 20 minutes. The rate of activity required in midcourse could, therefore, be the same or higher than in the boost phase. Of course, in a massive launch, the number of targets and decoys would be thousands of times larger.

Leverage is low in the midcourse, but midcourse defense does have the potential for being selective. Destinations of individual RVs can be determined once the RVs have separated from the bus.

Terminal Phase.–The terminal (or reentry) phase is very short. If hardened targets are defended, defensive intercepts can occur at

[7] Only redundant targets, where the loss of many or most can be tolerated, are logical candidates for preferential defense. ICBM silos are perhaps the best example, since only a small fraction of them still carry enormous destructive potential.

[8] RVs which have not been properly dispensed by the PBV will not be accurately aimed, although they may nevertheless be armed and left on a trajectory which will take them somewhere within the borders of the country being attacked. If their mission requires high accuracy, such RVs will have been rendered ineffective; if their mission merely requires that they reach some region of the country and detonate, they may still be able to accomplish their task.

fairly low altitudes, since hardened targets by definition are designed to survive nearby nuclear explosions. However, if soft targets are to be protected, intercepts must take place at a higher altitude.[8] As few as tens of seconds would be available between the time reentry began (or more accurately, the time that atmospheric effects begin to sort out decoys from RVs) and the time that terminal interceptors would have to be launched in order to destroy the RV at a sufficiently high altitude. However, the terminal defense would have almost 30 minutes to get ready to engage the RVs. Time pressures would be minimized if earlier phases had identified and tracked those RVs which they failed to destroy, and were able to "hand off" this trajectory information to the terminal defense. This tactic assumes good discrimination and kill effectiveness in the earlier layers.

Advantages and Disadvantages of Layered Defenses

Multi-1ayered defenses have the potential for performing much better than single layer defenses. First, several layers of moderate effectiveness which combine to produce a total defense of high effectiveness will, in general, be easier to design and build than a single layer having the same resultant effectiveness. Second, multi-layered systems, in theory, are more robust than single-layered systems, especially if each layer employs different technologies and different designs. In that case, offensive developments which degrade one layer might not severely affect later layers. Third, the presence of early layers—the boost and post-boost layers–reduces the burden on the later layers. The number of objects the midcourse defense has to handle is cut in half if the early layers kill half of the missiles. Finally, building several layers allows the designer to take advantage of whatever unique advantages each layer provides. For example, a multi-layered defense could have both the leverage of the boost-phase defense and the selectivity of the midcourse. A single layer defense could have only one or the other.

However, there are drawbacks as well as advantages to layered defenses. The most obvious problem is that four layers are likely to cost more than one layer—especially if the layers are completely independent—although perhaps less than a smaller number of layers which were as effective as the total of the four. Second, the degree to which the layers can combine to produce high effectiveness will depend on how independent the layers are. To take an extreme example, if all layers depend on the same sensor system and that sensor system fails, all the layers will fail. The same holds true for battle management algorithms or other shared resources. The leakage rates of the individual layers of a layered defense can be multiplied together to give the total leakage rate only if the individual layers are totally independent and share no common elements. Otherwise, leakage through early layers may not be fully compensated for by later layers.

The robustness of the system against the loss (or severe degradation) of one layer will depend on how much capacity is built into the system to compensate for that loss. The layers must be able to take advantage of the other layers without being overly dependent on them. For example, if boost and post-boost defenses permit twice the expected number of objects to reach midcourse, and if that in turn substantially degrades the midcourse defense's ability to sort objects, the midcourse may let through not only the additional RVs but also many of the ones it would otherwise have intercepted.

In practice, it will be impossible to know in advance exactly how effective any layer will be; there will probably be large uncertainties in predicting how well it will work against an actual attack. Those uncertainties, however, will be viewed differently by the two sides. From the defensive point of view, extra capacity will be required in each layer in order to hedge against the possibility that it (or the other layers) will not perform as well as anticipated. From the offensive view, however, uncertainties will make it more difficult to de-

'Even if the defensive interceptor is nonnuclear, the attacking warhead may be *salvage-fused* to detonate if intercepted. Therefore, intercepts must take place higher above soft targets than they need to above hardened ones.

stroy (or penetrate) the defense with high confidence.

The significance of a degradation in capability will depend on the goal of the defense. It makes little difference whether an ICBM silo defense is 40 or 50 percent effective. If one were only interested in providing a survivable deterrent, rather than defending populations, these concerns regarding the vulnerability of one of several layers would be relatively unimportant. However, the difference between a 90 percent effective city defense and a 99.9 percent effective city defense is a hundredfold increase in the number of weapons reaching U.S. cities; this could make the difference between the survival and the destruction of our civilization.

Individual Tasks of Each Layer

Each layer must perform the following tasks:

- *Surveillance and Acquisition:* Attacks must be detected, and the number, location, and probable destination of all threatening objects must be determined.
- *Discrimination:* Actual missiles, busses, and warheads must be distinguished from nonthreatening decoys and other debris.
- *Pointing and Tracking:* Targets must be tracked with whatever precision is required by the weapon designated to destroy that target, and that tracking information must be communicated to the defensive weapon.
- *Target Destruction:* A defensive weapon must deliver sufficient energy to a target rapidly enough to destroy it.
- *Kill Assessment:* Those targets that have been successfully destroyed-must be identified and distinguished from survivors. In addition, if it can be determined why a targeted warhead was not destroyed (incorrect pointing, for example), this information can be used for a subsequent attack.

The above tasks all involve processing either information or energy. Sensors collect signals or radiation emitted by or reflected from targets. These are processed to yield information about the individual targets. Sensor and data processing technologies are therefore crucial to an advanced ballistic missile defense. When targets have been identified and assigned to weapons systems, energy stored in the weapons must be converted to a form which can be delivered to the target in sufficient quantity rapidly enough to destroy it. Various types of directed-energy (beam) weapons and kinetic-energy (projectile) weapons have been proposed for this role.

Technological candidates for sensors, processors, and weapons are described in this chapter. The battle management issues involved in coordinating and integrating these "building blocks' into a complete, functioning system are also discussed, along with possible offensive responses or countermeasures. Some of the logistical issues involved in constructing and operating such a system are noted as well. Further discussion of the feasibility and operational issues is presented in chapter 8.

Weapon Kill Mechanisms

Introduction and Types of Kill

The Strategic Defense Initiative Organization is investigating the feasibility of many types of weapons. The type that has been publicized the most, possibly because it appears to be the most exotic, is the directed-energy weapon. Although this class of weapon is only one potential facet of the SDI, it could possibly become the centerpiece of some of the defensive layers. The advantage of such weapons is clear: killing energy is delivered at or near the speed of light, and, for typical BMD distances, arrives at the target in less than a tenth of a second.

Concepts under investigation in this area include several types of laser and particle beam weapons. For weapons purposes, the relevant criteria used to determine the usefulness of the different technologies mostly concern their ability to neutralize targets in a small amount of time (seconds, at the most). Another consideration is the capability for kill assessment after the target has been engaged. This latter question depends in part on the target; it may be a booster rocket stage, a post-boost vehicle, or an RV. Enemy satellites could also be targets.

There are three types of kill mechanisms by which directed-energy systems can act: 1) *functional kill,* 2) *thermal kill,* and 3) *impulse kill.*

The *functional kill* mechanism, pertinent to particle beam or microwave weapons, prevents an offensive weapon from operating correctly without necessarily destroying it. Subatomic particles with kinetic energies of a few hundred million electron-volts[10] (MeV) can penetrate at least several centimeters of dense materials, or tens of centimeters of typical aerospace materials. Therefore, sensitive electronic components deep inside the target can be altered or destroyed. However, it may not be immediately apparent to an outside observer that a kill has occurred. A kill of this sort may be referred to as a "soft," i.e., initially unobservable, kill.

To disable boosters by *thermal* means, a nominal range of 1 to 100 kilojoules of energy deposited per square centimeter (kJ/cm^2) of target has been taken as an estimate in the literature. This energy must be delivered quickly–if the time needed to deliver a lethal amount of energy is very long (hundreds of seconds or more), the heated area of the booster may have time to conduct away *much* of the energy being directed at it and may then not fail. The actual value of a lethal energy dose for a given target depends on many factors, including material, surface properties, and mechanical stress. This energy will raise the surface temperature of the target sufficiently to weaken or deform it, allowing internal forces to cause a catastrophic failure. The ability of a given technology to effect a thermal kill depends on the power levels attainable, the focusing ability of the weapon, and the distance from the target.

[10] An electron-volt is the amount of energy an electron can pick up from a l-volt battery.

Impulse kill does not achieve its goal by heating the target, but by depositing energy in a powerful pulse on its surface. A mechanical shock wave is driven through the target, collapsing it.

Lasers

A laser is a device which produces a coherent beam of electromagnetic radiation at a well-defined wavelength. Coherence means that all the waves of radiation are in step, crest-to-crest and trough-to-trough, and maintain this alignment over time. When they strike a surface, the effects are greater than would be the case for incoherent radiation. The intensity of incoherent radiation is limited by the temperature of the object producing that radiation; there is no such limit to laser radiation. The radiation may be in the infrared, visible, ultraviolet, or X-ray regions of the electromagnetic spectrum.

Lasing occurs when more of the lasing material's molecules (or atoms) are in an "excited" higher energy state, and fewer in a lower energy state, than is normally the case. When an excited molecule drops back to a lower energy state, it emits radiation at a precisely defined wavelength. This radiation stimulates other molecules to do exactly the same thing. They drop back to the same lower state, emitting radiation in step with the original radiation and having the same wavelength. This effect quickly spreads throughout the lasing materiaI (the *lasant),* and a laser beam is produced. Mirrors are usually placed at each end of a resonant cavity which contains the lasant. They reflect the radiation back and forth in order to stimulate further emission along a very narrow range of angles.

A major task is to arrange the molecules of the lasant so that there is a "population inversion"—i.e., so that there are more molecules in an excited state than in a state of lower energy. A suitable lasant must be found, and the energy needed to "pump" it—i.e., to raise its molecules to the upper laser state—must be provided. There are several ways to provide the energy for this purpose. Some lasers use chemical energy (in the form of a chemical reaction which produces molecules in an excited state); others use electrical energy. The characteristic wavelength produced depends on the material used as a lasant, and it is determined by the difference in energies between the upper and lower states.

The effectiveness of a laser as a beam weapon depends on the rate and amount of energy which can be delivered per unit area on a target. This quantity is determined by the laser power, the distance to the target, and the degree to which the beam can be focused on the target. Effectiveness also depends on the retarget time.

All electromagnetic radiation, even focused radiation, eventually spreads out with distance. This spreading, known as diffraction, results in a beam which becomes less intense as it travels out from its source; the maximum possible intensity of a laser beam (assuming the greatest possible degree of focusing) falls off as the square of the distance from the laser. The amount of diffraction depends on both the wavelength of the radiation and the diameter of the mirror, with the minimum possible spreading angle in radians" being equal to about 1.2 times the ratio of the wavelength of the radiation to the diameter of the laser aperture.[12] This angle of spreading is an ideal limit, assuming perfect optics and perfect focusing. An important consequence is that the smaller the wavelength, or the larger the laser mirror diameter, the less spreading occurs. To reduce diffraction, and therefore to reduce the beam size on target and deliver more energy per unit area, wavelength should be minimized and mirror size should be maximized.[13] Of course, in choosing these parameters, one is limited by physical and engineering constraints.

Smaller wavelengths, while allowing smaller mirrors for the same amount of spreading, also impose more stringent tolerances on the quality of the optics used. The size of the irregularities in the optics must be much less than one wavelength of the radiation used.

Aiming radiation at a moving target thousands of kilometers away requires highly accurate tracking and pointing. Typically, a beam spot of roughly a meter in diameter is envisioned for attacking today's missiles in the boost phase. To hit a target with an error of tenths of a meter at a distance of thousands of kilometers (km) requires aiming accuracy of about a tenth of a microradian. This is equivalent to hitting a television set in Los Angeles with a beam fired from directly over New York City.

In order to complete a thermal kill, the beam has to dwell on the target long enough to deposit a lethal amount of energy. Tracking accuracy must therefore be maintained over that interval. During one second, an ICBM may travel from 1 to 7 km (depending on when it is engaged) and can sweep through an angle (as observed by the laser weapon) of up to about 3,000 microradians.

Chemical Lasers:

Description. –Chemical lasers use the energy from a chemical reaction between two fuels to produce laser radiation. The most mature chemical laser technology for high-powered lasers is the hydrogen fluoride (HF) or the deuterium fluoride (DF) laser, in which hydrogen (deuterium) and fluorine combine to form hydrogen (deuterium) fluoride. Relatively high levels of power have already been produced in this type of laser, although a major scale-up from these levels is still needed

[11] One radian is an angle of 360/2 π (about 57.3) degrees. It is defined as the angle subtended by that portion of the circumference of a circle having a length equal to the circle's radius.

[12] Ashton Carter, *Directed Energy Missile Defense in Space,* background paper prepared for the Office of Technology Assessment (Washington, DC: U.S. Government Printing Office, April 1984), p. 17, takes the spreading angle to be 1.2 times the wavelength divided by the mirror diameter. It is noted that the full angle subtended by the null ring of the Airy disk diffraction pattern requires a multiplier of 2.4. However, most of the energy is contained within a diameter only half as big; therefore, 1.2 is taken as the multiplier. This assumption is favorable to the laser technology, since not all of the beam's energy is contained within this angle; the lethality of the actual beam will thus be slightly less than the estimates in this section.

[13] For example, the minimum diffraction angle for a wavelength (in the infrared) of 3 microns (millionths of a meter), using a perfect mirror 10 meters in diameter, would be 3.6 x 10-7 radians, or 0.36 microradians. Even this small angle, however, would result in a beam spot of about 1 meter diameter at a distance of 3,000 km.

before power levels necessary for BMD can be obtained. The HF (DF) wavelength is 2.7 (3.8) microns (millionths of a meter). Other chemical lasers at different wavelengths are under consideration, such as oxygen-iodine (1.3 microns wavelength), iodine fluoride (0.65 and 0.72 microns), and nitrogen oxide (0.24 microns).

For illustrative purposes, we can look at potential requirements for an HF laser. As mentioned above, the diffraction phenomenon sets a lower limit on angular spreading. Approaching this limit requires a significant technical effort; for illustrative purposes, the following example assumes that this theoretical limit can be attained in practice.

The beam from an HF laser with a 10-meter diameter mirror would have a minimum angular spread of 1.2 x 2,7 x 10 ‘/10 = 0.32 microradians. At a distance of 1,000 km, therefore, a spot size of about 0.3 meters diameter would be produced. A laser of 20 megawatts (MW) output power would have an intensity of 25 kW/cm^2 at this distance. A watt is a joule per second. Therefore, exposures of 0.04 to 4 seconds would be required to reach the level of 1 to 100 kJ/cm^2. At a distance of 2,000 kilometers, exposures four times as long would be required. At 100 kilometers, the required times would be 100 times shorter.[14]

The length of time required to deliver a lethal amount of energy is inversely proportionalto the power of the laser, if the other parameters are held constant. Thus, if a 20 MW laser were to be replaced by a 40 MW laser of the same wavelength and mirror diameter, the required dwell time would be cut in half.

“The device parameters used here are only intended as examples. Although relatively powerful H F lasers have been constructed and operated, none has yet come close to a 20 MW rating. The largest telescope mirror in the United States, at the Mt. Palomar observatory, is 200 inches (5.08 m) in diameter; a telescope using a 10-meter diameter mirror is currently being designed by astronomers at the University of California. The diameter of the Space Telescope mirror is 2.5 meters. No mirrors of this size have yet handled megawatts of electromagnetic radiation. There are, however, no obvious technical bars to prevent either the laser or the mirrors from being developed.

We could also increase the diameter of the mirror to extend lethal range. By doubling the mirror diameter to 20 meters, the spreading angle is reduced by a factor of 2, and the delivered intensity increases by a factor of 4. Therefore, the lethal range of a laser weapon grows as the laser power and as the square of the mirror diameter.

Issues.—Several technical questions must be resolved in order to demonstrate the feasibility of the chemical laser approach. The required laser power levels must be approached closely enough to assure that no significant engineering problems will prevent scaling up to the full required power. Mirrors of the required dimensions and quality must be constructed and tested at high power levels. The total system of the required power, optical quality, and physical size must be robust enough for transport to on-orbit position. The atmospheric absorption of HF infrared radiation does not permit ground-basing (although this is not necessarily true for other wavelengths under consideration). Finally, the physical characteristics of the system should permit the installation of many units in orbit, given the transport shuttle capabilities likely to be available within two decades or so. To deal with Soviet countermeasures making their boosters more resistant to attack, it would be necessary to increase greatly brightness levels over those needed to counter existing Soviet ICBMs. Such devices would be several orders of magnitude beyond present capabilities, and would require reducing the laser wavelength, increasing laser power, increasing the size of the optics, or some combination of the three.

Excimer Lasers:

Description. –Another promising area of laser research is the excimer laser. An “excimer” is an excited dimer, or two-atom molecule, typically consisting of a noble gas (e.g., argon, krypton, xenon) atom and a halogen (e.g., chlorine, fluorine) atom. In an excited state, these two atoms can form a bound molecular system. When the molecule drops to a ground state, it rapidly disassociates into two separate atoms: noble gases do not form stable molecules in the ground state. The excited population of excimer molecules is produced by a pulsed electrical discharge process, rather than by a continuous chemical reaction. The light produced, therefore, occurs in pulses. After the pulse of laser radiation is produced, the process repeats with a new electrical discharge, leading to another "pumping" of excited dimer molecules. Relative to HF lasers, excimer lasers have the advantage of a shorter wavelength (typically 0.3 to 0.5 microns in the near ultraviolet to visible region of the spectrum), which greatly reduces the size requirements on mirrors. As a result, however, the optical requirements for mirror uniformity are that much more stringent.

The reduced requirement on mirror size, if such mirrors can be made, is a significant advantage over longer wavelength options. The fact that the wavelength is only about one-tenth that of infrared lasers means that, for a given range, the mirror's diameter need only be one tenth that required for chemical lasers. The area, then, would only be one-hundredth as large. Since the thickness of a mirror, including its support structure, can be kept fairly constant over a substantial range of diameters, its weight will be approximately pro portional to its area. Excimer laser mirrors, then, with one-tenth the diameter, may weigh only on the order of one-hundredth as much as HF laser mirrors with the same capability. To see the advantage of the shorter wavelength laser, consider the hypothetical example of placing a laser in geosynchronous orbit where it could always see all of the Soviet missile fields. The distance of effectiveness would have to be about 40,000 kilometers. At that range, an HF laser would require a perfect mirror of about 130 meters in diameter to keep the beam size down to 1 meter in diameter at the target. This is infeasible for the foreseeable future. However, an excimer laser would require a mirror of the order of "only" 15 meters in diameter for the same size beam spot.

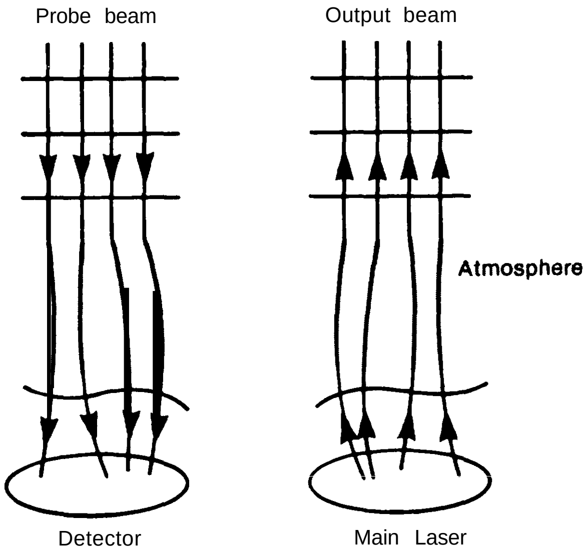
Placing any sort of a BMD-capable laser in geosynchronous orbit may, however, be impractical. Instead, a ground-based laser might be aimed at one or more mirrors in geosynchronous orbit. This scheme would have the obvious advantage of utilizing a ground-based power source, allowing continuous operation for long periods of time and reducing the weight placed into geosynchronous orbit. There would have to be several lasers, since cloud cover could render some of them useless at a given moment. The geostationary relay mirrors would reflect the beams from the ground lasers onto smaller battle mirrors in low-earth orbit, which, in turn, would track individual targets and redirect the laser beam to them.[15] The geostationary relay mirror would have to be much larger in diameter and much more complicated if it were to attack boosters directly without the help of lower orbit battle mirrors. Using the battle mirrors, the relay mirror need not track individual targets at all. A constellation of battle mirrors would be needed so that enough of them could always be on station to deal with missiles launched from all possible launch sites. Note that this scheme is impractical for long wavelength lasers since the required mirror sizes are so large.

Even at short wavelengths, a very powerful laser would be needed in order to travel through the atmosphere and bounce off several mirrors while retaining its lethality. (The additional spreading introduced by making the beam travel out to geosynchronous orbit and back can be compensated for by making the relay mirrors sufficiently large in diameter.) A very large quantity of power (hundreds of megawatts) would have to be available on short notice to each of the ground-based lasers.

In order to compensate for atmospheric distortions, a technique known as "adaptive optics" is being developed. A pilot laser beam

[15] Relay mirrors could be in lower orbit than geosynchronous, and could therefore be somewhat smaller than they would have to be if they were in geosynchronous orbit. However, since mirrors in lower orbit would not remain over the same spot on the ground, enough would be required so that one or, preferably, more would always be in a position to relay the laser beam to an appropriate battle mirror. In addition, if the relay mirror orbits were too low, more than one bounce would be required to direct the beam from a ground laser to a battle mirror on the other side of the Earth.

Figure 7-2.—Compensating for Atmospheric Distortion With Adaptive Optics



Phase information from an incoming probe beam reveals atmospheric distortion. Large ground-based laser beam is distorted in the opposite sense to cancel out the atmospheric effects.

SOURCE Off Ice of Technology Assessment

sent from the space mirror would be detected at the ground-based laser. Information from the beam would reveal the pattern of phase shifts caused by atmospheric distortions. As a result, corrections could be applied to the beam generated by the ground laser, possibly by distorting a mirror at many points over its surface, in such a way as to compensate for the atmospheric effects. Atmospheric disturbances typically occur over times which are on the order of tenths of a second, during which time the pilot beam can travel through the relevant part of the atmosphere (the 20 km nearest the surface), the main laser beam can be corrected for the distortion, and the beam can propagate back out through the atmosphere, all before the disturbance changes significantly. As atmospheric distortions change, the optics would automatically compensate.

Issues. –To determine the feasibility of this ground-laser/space-mirror approach, the adaptive optics method of compensating for atmospheric distortion must be examined for high power levels over long distances. The ability to compensate for atmospheric effects in the presence of such an intense beam has not yet been demonstrated. Mirrors of the required *size* and robustness, and satisfying the exacting tolerances, must be constructed. They must withstand intense laser beams without distorting significantly or failing. Unlike the HF case, only a few very large ones need be made. However, many more smaller battle mirrors, each with a diameter of about 5 meters, would be needed. With countermeasures by the offense, this number could increase further.

A possibly significant problem for this system, as well as any other directed-energy system, is the need to retarget from one object to another in 1 second or less. This requirement may be quite difficult to meet; greater retargeting times would not rule out given weapons systems, but could imply the need for far larger constellation sizes (see section on System Architecture, p. 179 ff.). If only small retargeting angles are needed for a single satellite, fast retargeting may be easier to attain; this possibility is under investigation.

Another issue to be resolved is the ability to produce excimer lasers of the power levels required. Current excimers are several orders of magnitude smaller than requirements for SDI applications. Large amounts of power will have to be delivered in short pulses. The required power levels will depend on the results of research in the various fields. Excimer lasers tend to have a high weight-to-output power ratio, which would make them more problematic for space-basing. This would not affect a ground-based mode, where weight is less of a consideration.

Free-Electron Lasers:

Description. –When the paths of charged particles are bent by a magnetic field, they emit radiation. The recently developed free-electron laser uses this principle in an innovative way to produce laser radiation. A beam of electrons is passed through a periodically-varying magnetic field. The radiation produced can provide an intense coherent beam. In the free-electron laser, the interaction of the electrons and the magnetic field replaces the

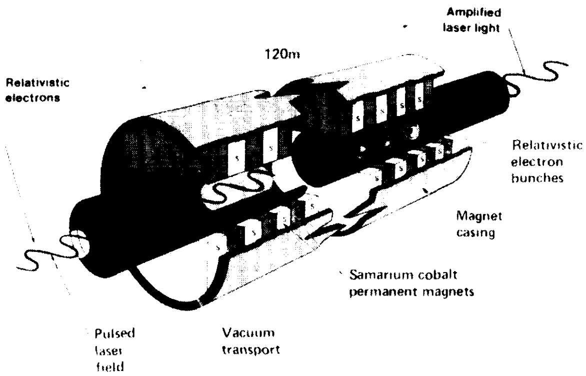


Photo credit: Lawrence Livermore National Laboratory

A schematic drawing of a free-electron laser with field-alternating "wiggler" magnets. The magnetic field forces the electron beam to follow a sinusoidal path, causing them to emit laser radiation. In this drawing, a low-power laser beam is amplified by the electrons.

excited energy levels of a lasant as the source of coherent radiation. The wavelength, which depends on the periodicity of the magnetic field and on the electron energy, can be changed as desired by varying either one. Such a laser operating in the visible could be ground-based, using space-based reflectors to reach targets beyond the horizon (see previous section). High energy efficiencies could also permit the possibility of space-based lasers.

In addition to the advantages of good beam quality and high energy efficiencies which are obtainable, the free-electron laser also has the advantage of being able to use a relatively mature technology: that of the particle accelerator.

issues.—The process is potentially more energy efficient than other schemes, and it has the significant advantage of frequency tunability. The technology is in its infancy, although progressing rapidly, and much research effort is needed to determine its potential for application as a directed-energy weapon. The SD I program is investigating whether power levels can be scaled up by many orders of magnitude at useful wavelengths. It is also studying, as in the case of excimer lasers, whether window and mirror materials can be developed which are capable of withstanding the intense laser beam while maintaining the required optical quality.

X-Ray Lasers:

Description.—Like the free-electron laser, X-ray lasers are relatively new. The "pumping" of the lasant material to an excited state would be accomplished by intense sources of radiation, such as a nearby nuclear explosion, an optical laser, or some other source. Should a nuclear explosion be used to pump an X-ray laser, that laser could be lethal to a target even if the energy conversion process were very inefficient since the energy produced in just a small nuclear explosion is still very large. The U.S. Department of Energy is investigating the feasibility of developing nuclear-pumped X-ray laser weapons; however, it has classified virtually all details of this research other than its existence.

An advantage of a nuclear-pumped X-ray laser weapon would be that it would have the potential for killing many targets using multiple beams, providing high leverage and countering attempts to saturate the defense. A disadvantage of such a weapon would be that it could be fired only once—the explosion that powered such a weapon would very shortly afterwards destroy it. Such a weapon would not be able to assess damage and fire again, although a second weapon could certainly do so.

There are natural limits on the distance to which X-rays can propagate within the atmosphere, where they are rapidly absorbed. Since an X-ray laser used for a boost-phase defense must therefore wait for a booster to climb higher than the minimum altitude to which the X-rays can reach (which depends on parameters such as X-ray intensity, wavelength, and incident angle), the time available for the defense to act is reduced.

A conceivable mode for use of X-ray lasers, assuming that they would be developed as weapons, is the pop-up technique. The relative ly low weight of such a weapon system could contribute to the desirability of such an architecture. The lasers could be deployed on specially developed submarine-launched missiles.

When the defense receives notice of an attack, it could launch its pop-up weapons to an altitude sufficient to attack one or several ICBM boosters or post-boost vehicles after they have risen above the minimum engagement altitude. In such a system, the weapons would not have to be deployed in space, avoiding a serious vulnerability problem faced by space-laser or ground-laser/space-mirror schemes. Also, deploying nuclear-pumped weapons on submarines, rather than in space, would avoid violating the Outer Space Treaty (see appendix C). Other military applications of this technology may be possible, but are beyond the scope of this report.

Issues.–The first question to be resolved is whether the X-ray laser can be developed to the point of use as a weapon. The efficiency of the conversion process and the possibility of achieving adequate levels of brightness are major issues. If a pop-up mode were to be investigated, secondary systems-related questions would also arise. Since the X-ray lasers would have to be popped up after a Soviet launch, their boosters would have to be substantially faster and more rapidly accelerating than the Soviets', which would have a head start. This means that the pop-up would have to burn much more fuel per unit payload weight than its target. A system would have to be developed with an almost instantaneous response time, including high-quality communications links between the orbiting satellite sensors and the submarines. Further, a submarine, which might only be able to fire one rocket at a time with a delay between successive launches, could become a "sitting duck" once it had revealed its location by firing. The practicality of a global scheme involving pop-up X-ray lasers of this type is doubtful.

Particle Beams:

Description. —Unlike electromagnetic radiation, which consists of pure energy, beams of subatomic particles consist of bits of matter. They can be protons, electrons, neutral atoms, heavy ions, or more exotic types. They are accelerated to velocities approaching the speed of light by electric fields in particle accelerators. Accelerators for diverse types of particles exist in various sizes all over the world. They are used for fundamental research in the areas of solid state, nuclear, and, above all, high energy physics. It is known and understood how to produce and accelerate all manner of atomic and subatomic particles. The challenge for weapons purposes is to produce beams of very high intensity which are also extremely collimated-i. e., which are narrow and have a small spreading angle, so that the particles move in very nearly parallel paths. Accelerators producing such beams must be light enough to be placed in space economically, and they must be very reliable.

In order to accelerate particles with electric fields, one must use charged particles. However, over long distances, a charged beam will bend in the Earth's magnetic field, presenting formidable difficulties in targeting. Inhomogeneities in the Earth's field can render it virtually impossible to direct a beam at a target spot of a meter size, or so, at the distance of thousands of kilometers.

Preliminary experiments in laboratories have led to some hope that for low-Earth orbit altitudes, it maybe possible to use a charged beam by means of the following mechanism. A laser first ionizes a straight path through the rarefied near-space environment. Then, an electron beam is fired along this channel, with the positively charged gas ions providing an electrostatic restoring force which compensates for the bending forces of the Earth's magnetic field. Demonstrating the ultimate practicality of such a scheme requires further resolution of a number of issues.

A less exotic solution is to produce a neutral beam, unaffected by magnetic fields, which will travel in a straight line and be more easily directable to a target. To make a neutral hydrogen beam, for example, a large number of hydrogen ions is created by attaching an extra electron to neutral hydrogen atoms. The charged ions (H^-) are then accelerated by electric fields, and, after exiting the accelerator, are neutralized by one of a variety of techniques. The extra electron can be knocked off by passing the ion beam through a small amount of matter, for example, or it can be stripped off by means of appropriately tuned laser radiation. In either case, a set of neutral hydrogen atoms is again produced. Now, however, they are traveling together in very large numbers at nearly the speed of light.

This beam of neutral particles contains a significant amount of energy, can penetrate several centimeters into virtually any material, and can penetrate typical aerospace materials to a depth of tens of centimeters. Because of this penetrating power, neutral particle beams may be difficult to countermeasure. The hydrogen atom's electron is quickly stripped off as the atom enters the target. The bare proton which remains deposits its energy more or less uniformly along its path through the material, with a slight enhancement in the small region where it finally comes to rest. If the beam strikes electronic circuits, such as those in guidance systems, they can be fatally altered or destroyed, rendering the target "stupid" and unable to function in its programmed way. An energy deposition of some tens of joules per square centimeter could be sufficient to destroy unprotected electronics in a target. The deliverable energy requirements for this type of weapon, therefore, are considerably less stringent than in the case of lasers, where 1 to 100 kJ/cm^2 (10 to 1,000 MJ/m^2) may be required. At higher levels of neutral particle beam energy deposition, objects can be melted and explosives detonated.

Such a weapon, however, can work only outside the atmosphere: even a small amount of air will strip off the electrons, resulting in a beam of charged protons. These will be bent by the Earth's magnetic field and will also be scattered by collisions with atmospheric molecules. As a result, the beam will not be effective against targets below about 100 km.

Issues.-The energy of each particle in a particle beam is not a serious problem. Energies of several hundred million electron-volts are usually discussed in this context, which are well within the limits of current capabilities for the particles in question. In fact, the largest accelerators today are able to reach energies a thousand times higher, although at lower intensities.

Individual particle energy, however, is only one of the parameters that determines a particle beam's effectiveness as a weapon. Another is the beam *current,* which is proportional to the number of particles per second in the beam. The beam current (in amperes") multiplied by the energy of each particle (in electron-volts) gives the total beam power (in watts). The brightness of a particle beam, which determines the power that can be delivered per unit area at a given distance, depends on the beam power and additionally on how tightly the beam can be focused. At present, particle beams are closest to the required level of brightness of all the directed energy options generally discussed for SDI.

One problem with a particle beam weapon will be kill assessment. A beam intensity sufficient to disable its target electronics may not be sufficient to produce external effects which are immediately observable. This drawback might impose severe problems regarding targeting decisions if neutral beams are to be used in such a "soft," functional kill mode. To provide externally observable effects, brightness levels perhaps a thousand times greater might be required, unless the guidance system of a booster or post-boost vehicle were struck in such a way as to cause obvious trajectory modifications.

A related problem is tracking the beam. If the beam misses the target, it will be very difficult to know where it went; even if it strikes the target, it may not be visible at "soft" kill intensities. "Open-loop" pointing, in which one measures the direction of the beam as it exits the accelerator with great precision, is a possible solution, but it remains to be demonstrated.

A further problem would be presented if the electronic components of beam weapon targets were hardened against radiation. Circuits using gallium-arsenide (GaAs) technology could be as much as 1,000 times more resistant to radiation than commonly existing cir-

"Neutral beams, which are not charged, technically carry no electrical current. The intensity of a neutral particle beam in amperes is the electrical current that the beam would carry if each particle in it had the charge of one electron.

cuits based on silicon technology.[17] Such hardening could increase resistance to ionizing radiation by a factor of up to 1,000, stressing further the energy delivery requirement of a particle beam weapon. The system hardness, however, may not be increased by the same large factor as the component hardness.

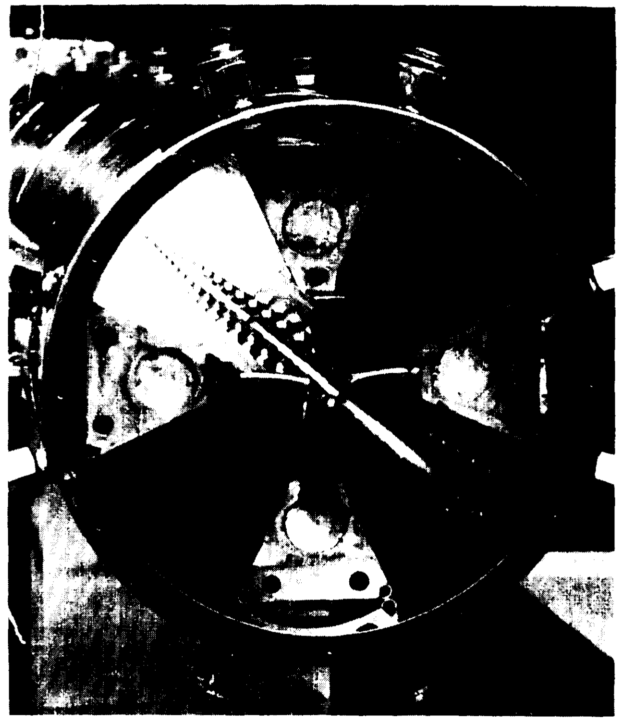
Another serious issue is whether an accelerator can be constructed which will be light enough to permit many to be placed in orbit, and which will retain the ability to function reliably after long periods of dormancy. While current Earth-bound accelerators approach the necessary beam intensities, they are large and heavy and also require maintenance and repair at irregular intervals. Space-qualified equivalents would need to be much lighter, much more reliable (since they would be harder to fix), and like other space-based assets, protected against attack.

Kinetic Nonnuclear Kill

Boost, Post-Boost, and Midcourse Phase:

Description. –A classic method of destroying a target is simply to hit it with another object having a large velocity relative to the target. This method utilizes kinetic energy, or energy of motion, and has been used for a good many millenia in forms such as rocks, catapults, arrows, and bullets. Missiles and RVs travel at high speed, typically several kilometers per second; they can be killed quite effectively by colliding with something else moving at a significantly different velocity. The problem lies in arranging the collision-in reaching the missile or warhead and hitting it.

This technique could be implemented by a constellation of space-based battle stations, each containing a large number of small rock-



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ets or electromagnetically launched projectiles. Satellite sensors would detect a launch and would hand tracking information over to the battle station. The rockets would be assigned to, aimed at, and launched towards their targets. When close enough, homing detectors on the projectiles would be used to direct them to their targets. The kill could be by means of striking the target directly or by detonating an explosive near it, sending fragments into it. (Outside the atmosphere, of course, an explosion does not produce a shock wave, so the fragments would be necessary for a kill.)

For attacking boosters, the bright infrared signal from the rocket plume serves as a target for a short-wave infrared homing device;

[17] Gallium arsenide (GaAs) technology shows promise for making circuits which are faster, as well as much more radiation-resistant, than circuits based on silicon technology. It is therefore a topic of intense research interest by the Department of Defense as well as by private industry. GaAs technology will likely be considerably more expensive than equivalent silicon circuits, primarily because silicon technology has had the benefit of decades of intensive research. However, it will probably become the technology of choice for many applications requiring speed or radiation-resistance.

however, the projectile will probably need to correct for the distance between the booster body and that portion of the exhaust plume flame or engine nozzle which emits most brightly in the infrared. For post-boost vehicles or RVs, short-wave infrared sensors could not be used since the PBVs (except during short bursts of their rocket motors) and RVs would be at much lower temperatures than the boosters and would radiate much weaker signals at longer wavelengths. Cooled, long-wave infrared detectors could be used during the post-boost and midcourse phases, but other sensing devices might be required because the relatively cool targets may not be readily detectable by infrared means against the background of the Earth. Short- and long-wave infrared detectors, along with other sensors, are discussed further in the following section on sensors (p. 159 ff.).

Issues.–A major question is whether the space-based rocket could reach the booster before burnout. Basing at altitudes of about 400 kilometers has been discussed. Soviet SS-18 rockets burn out in about 300 seconds at an altitude of about 400 km. If the satellite platforms carrying the interceptor rockets were based at an orbital altitude of about 400 km, an interceptor could travel horizontally for up to 300 seconds to reach a booster if it could be launched at the same time that the booster was. If the platform is based at a higher altitude, the interceptor will have to shoot down to reach the booster and will not have as far a horizontal range.

If the interceptors had a burnout velocity of 10 km/sec,[18] each could travel about 3,000 km in 300 seconds, giving them a useful range. A terminal velocity this high for a chemical rocket would imply a very small ratio of payload weight to fuel weight; this would be compensated for, in part, by multi-staging, but the need for a low-cost lift capability to place the interceptors and their fuel in orbit would nevertheless be manifested.

[18] For comparison, a satellite in low-Earth orbit travels at about 8 km/sec.

If the length of the boost phase were reduced, interceptor ranges would be correspondingly reduced. The MX missile burns out in about 180 seconds. The Soviets are currently testing an MX-like ICBM (the SS-X-24) which would therefore effectively shorten the maximum interceptor range from that attainable against an SS-18. A fast-burn booster would reduce the effective range still further.

Another issue for infrared homing devices involves the ability of such detectors to function in the upper atmosphere. Since friction with the atmosphere will heat the skin of the interceptor rocket, any infrared detector will have to look out through a very hot window. Windows which do not emit much infrared radiation even when heated to high temperatures will be required. If homing interceptors cannot be made to operate in the atmosphere, it will become necessary to wait until boosters have left the atmosphere before intercepting them. Alternatively, interceptors might dispense with homing sensors, being guided by commands sent from other satellites better able to track the boosters ("command guidance").

Homing outside the atmosphere has already been demonstrated in a test configuration. The Homing Overlay Experiment conducted by the U.S. Army in June 1984 demonstrated the ability to find a cool target outside the atmosphere against the cold background of space, and to home in on it accurately enough to collide with it. Similar technology is utilized by the U.S. Air Force's air-launched ASAT weapon.

Interceptors could attain higher velocities using a developing technology: the electromagnetic railgun. An intense magnetic field is used to impart large velocities to electrically conducting projectiles; the conductor can be formed by ionizing a substance which might be an insulator in its normal state. Speeds of greater than 20 km/sec or more are envisioned. Such techniques would appear promising because they could greatly extend the range of interceptors based in space. However, attaining such a high velocity by the time the projectile has left the gun requires accelerations hundreds of thousands of times that of gravity.

Problems to solve, besides the actual proof of principle at these high velocities, are the development of large power sources, power delivery in short pulses, good recoil momentum compensation so as not to degrade pointing capabilities, and the development of materials and guidance systems of very low mass which can survive the rapid accelerations needed. The ability to refire rapidly and accurately would also have to be developed.

Terminal Phase:

Description.–In the terminal intercept phase, kinetic-energy interceptors could be very high acceleration rockets located near the sites to be defended. If nonnuclear, they would kill by striking their targets or by detonation and fragmentation near the target. Phased-array radars (electronically steered and able to shift rapidly from one target to another) would track RVs and decoys and give pointing information to the interceptors, which would then home in on their targets with radar or infrared sensors.

Another possible technique is the "swarmjet" proposal. A large number of small rockets is fired in the direction of an incoming RV towards a region 50 m in diameter at a range of 1 km from the defended site. If properly timed, the swarm would have a high probability of destroying the RV. Since intercepts take place close to the ground, decoys will have already burned up during reentry and will not be a problem. However, the attacking warhead may be salvage-fused to detonate when intercepted, and since intercepts will take place relatively close to the defended object, a "swarmjet" defense would only be suitable for defending hardened targets able to survive a nearby nuclear explosion.

Issues. –The ability of a nonnuclear homing device to kill an RV outside the atmosphere has been shown. However, in addition, either the interceptor or (more likely) the overall battle management system must be able to discriminate between decoys and RVs (see discussion on discrimination, p. 162 ff.). For intercepts deep within the atmosphere, the atmosphere itself will screen out decoys.

Cost-exchange issues will be very important. For a given hypothetical defense system, the cost of large numbers of interceptor vehicles will have to be compared to the cost of additional incoming RVs1. Crucial to the cost calculations is the defensive system's footprint, i.e., the size of its defended area. The larger the footprint, the fewer systems are needed.

Overall, the state of the art of terminal interceptors, with the associated sensors and battle management systems, is closer to practicality than many other BMD technologies. However, these technologies at present are best applied to hardened targets. Discrimination is easier because intercepts can be delayed, and a far smaller volume of space would have to be covered. Near-term technology may be capable of defending hardened targets against a significant fraction of incoming RVs. However, the detonation resulting from the first intercept (in case the target were salvage-fused, giving a nuclear explosion upon impact) could make subsequent intercepts difficult. These problems could be mitigated by hardening sensors and by providing high levels of redundancy.

Interceptors would themselves have to be placed in hardened sites in order to remain operational in the case of a nearby nuclear explosion. The survival of some fraction of the targets could thus probably be assured, unless a very large number of RVs per target were attacking.

Soft targets, however, would be more difficult to defend. As has been stated, the higher intercept altitudes needed to protect soft targets make discrimination harder and also require defending a much larger volume.

Nuclear Kill:

Description. –The discontinued U.S. Safeguard ABM system used a nuclear warhead to kill incoming RVs. Such a system was desirable when homing systems could not approach closely enough to kill by impact or by explosion and fragmentation. The Low Altitude Defense System (LoADS), which used nuclear-armed interceptors for protecting hard

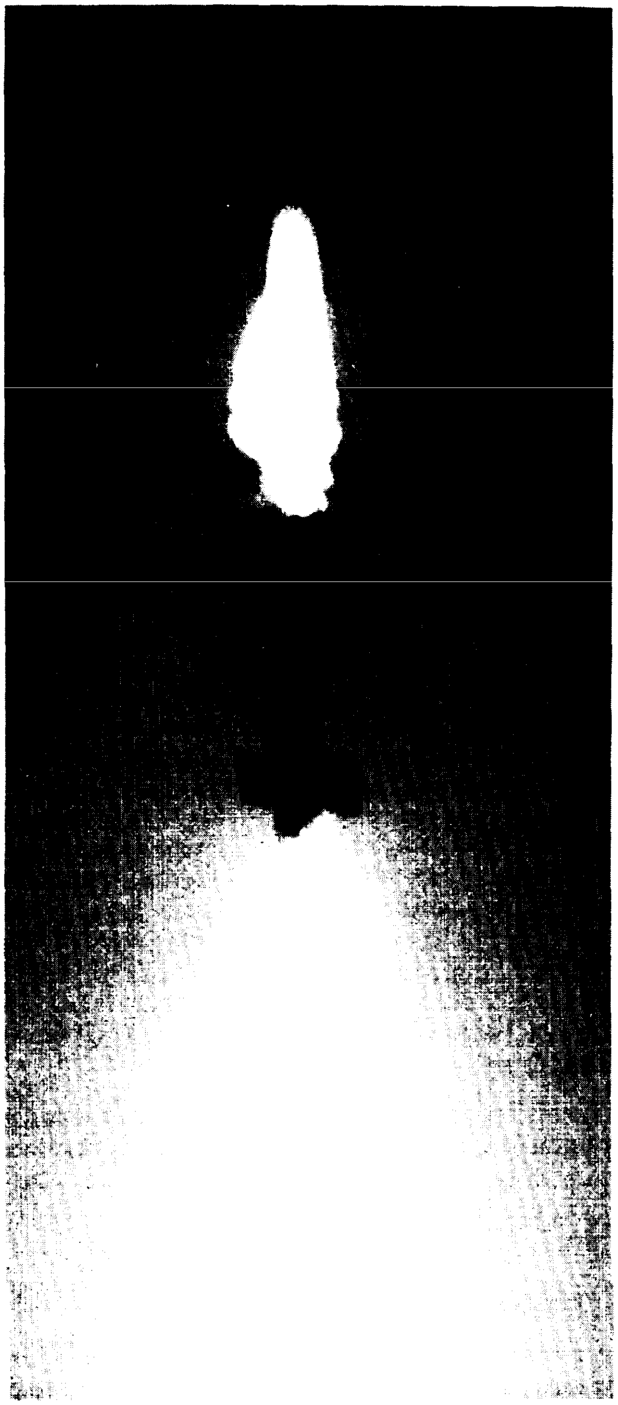


Photo *credit: U.S.* Department of *Defense*

Launched in November, 1984 from White Sands Missile Range, New Mexico, as part of the Small Radar Homing Technology (SRHIT, pronounced "S-R-hit") Program. A novel steering steering system is being used.

targets, had been under development until it was recently reemphasized under SDI. In principle, nuclear-armed missiles, representing a mature technology, could soon be operationalas elements of a terminal defense. Although major uncertainties still remain concerning the operation of such a system in the presence of many nuclear detonations, improved sensors, radar tracking, and communications would resuit in a more effective system now than could have been built in the early 1970s. These improvements would make nuclear interceptors a possible fall-back position for terminal defenses, in case serious impediments develop in adapting nonnuclear kill technologies for that purpose. For example, maneuverable reentry vehicles (MaRVs) might be able to evade interceptors to the extent that a nonnuclear kill vehicle could not approach within lethal range. The greater kill radius of a nuclear warhead might compensate for inability to achieve a close approach.

There could also be uses for nuclear kill against space-based defenses. Space mines, or weapons placed in orbit with the purpose of detonating on command to destroy enemy battle stations or to neutralize satellite sensors, could be nuclear-armed. They could also be salvage-fused so that, once within lethal range of a potential target, they could destroy that target even if attacked themselves.

In terms of killing attacking missiles or RVs, nuclear kills maybe less desirable, since they might not destroy more than one target at a time but could complicate other defensive actions by damaging or blinding elements of the defensive system.

Issues.—When using nuclear interceptors in the terminal phase, difficulties could arise from collateral damage or blinding of the defense's own radar tracking system and communications. Such use implies the need for hardened electronics, robust radar tracking, and effective battle management to minimize collateral damage. Homing systems that would permit use of very small nuclear weapons could mitigate some of these effects, particularly for exoatmospheric interception. If incoming missiles are salvage-fused, however, the environment would be stressful to defensive battle management whether or not the defenses use nuclear-armed missiles. It should be remembered that an advantage of nuclear kill is that the technology is essentially currently available.

Sensors and Data Processing

Advances in sensors and in data processing technology-in the ability to acquire and manipulate information–have had at least as much to do with the resurgent interest in ballistic missile defense as have advances in weaponry. In addition to their key roles in BMD technologies, sensors and data processors probably have greater general application than advanced weapons concepts in other military (and of course in civilian) applications.

All of the functions of a BMD system, save target destruction, involve primarily sensors and processors. As sensors acquire more and more data and incorporate greater amounts of processing directly within the sensing components, it becomes increasingly difficult to separate these two functions. Perhaps a better breakdown would be sensors (including processing), and other data processing activity, such as battle management or command and control. Battle management will be discussed in a later section on "System Architecture"; the following discussion will concentrate on the data acquisition and manipulation performed by the sensors of a ballistic missile defense system.

Sensors can further be broken down into surveillance and acquisition sensors, whose primary function is to notice threatening objects and determine their approximate location, and higher resolution sensors, which investigate these objects in much greater detail.

Surveillance and Acquisition

There are a number of technological candidates for performing surveillance and acquisition functions. They are distinguished in this section by the phase in which they would most appropriately be used. (Sensors used for discrimination, as opposed to surveillance, are discussed in the next section. Seep. 162 ff.).

Boost Phase.–The hot gases exhausting from an ICBM booster motor emit hundreds of kilowatts at short- and medium-wave infrared (SWIR and MWIR) wavelengths of a few microns. This radiation can be detected by sensors at great distances. Both the United States and the Soviet Union now obtain early warning of ballistic missile launch by sensing the infrared radiation from these exhaust plumes; U.S. early warning satellites are at geosynchronous orbit 36,000 km above the Equator, while their Soviet counterparts travel in highly elliptical orbits which are at even higher altitudes when over the United States.

The launch detection sensors characterize the approximate size and trajectories of the ICBM attack in order to "hand off" the suspected targets to systems having higher resolution, which can examine the objects and aim at the threatening ones. In addition, some discrimination can be done at the earliest stages of detection, depending on the spatial and spectral resolution of these early warning sensors and the image processing software used with them. If the infrared sources are not moving, or are not moving towards defended areas, then they do not pose a threat.

If a boost-phase layer is present in the defense system, it will only have a few minutes after launch detection in which to destroy the climbing boosters. Once infrared sources are detected and are identified to be ICBMs, the detection sensors will "hand off" their tracks to the pointing and tracking sensors associated with each weapon system.

Post-Boost and Midcourse Phases.—Surveillance requirements become considerably more difficult in the post-boost and midcourse phases because the objects to be detected are no longer necessarily associated with conspicuous infrared sources. By the end of the boost phase, all the ICBM booster stages have burnt out and dropped off, leaving the post-boost vehicle. The PBV then dispenses reentry vehicles and decoys, changing course slightly to aim each weapon individually before letting it go."

The PBVs, decoys, and deployed RVs can be detected by their own radiation, rather than that emitted by their hot exhaust gases. Objects more or less at room temperature emit long-wavelength infrared (LWIR) radiation having wavelengths mostly near 10 microns. (By comparison, the Sun is hot enough to shine in the visible portion of the spectrum, with wavelengths primarily near 0.5 microns. Rocket exhaust, which is cooler than the surface of the Sun but is still much hotter than the PBVs, RVs, and decoys, emits radiation primarily in the short- and medium-wave infrared wavelengths of a few microns.)

LWIR radiation can be detected by sensors which are cooled to near absolute zero in order to prevent their own radiation from swamping the signal.[20] Such sensors can search for objects already in space (deployed warheads, satellites, decoys, or debris) without having to observe a launch, and they can provide independent backup for the launch surveillance systems.

In addition to detecting deployed warheads which may have escaped launch detection, a BMD system must do space surveillance in order to keep track of threats to itself. Before launching nuclear weapons against terrestrial targets, the offense may choose to attack the defensive system directly in order to damage or disable it. Therefore, the BMD system must keep track of satellites which could attack from a long range (those suspected of holding nuclear warheads or directed-energy weapons), objects which need to approach closely in order to attack (ground-based interceptors, or space-based nonnuclear ones), and satellites called space mines which, if allowed by the defense, could constantly trail system components and detonate on command, destroying both themselves and the BMD component.

LWIR sensors are useful for such space surveillance systems. Any object in space for a long enough period of time will reach a steady temperature when the rate at which it absorbs energy (either from the Sun or radiated up from the Earth) equals the rate at which it emits LWIR radiation. The amount of absorbed power, which tends to heat the object up, depends on the surface properties and the surface area of the object; the amount of radiated power, which tends to cool the object down, depends on its surface properties, its size, and its temperature. For example, the average temperature of the Earth itself is set by the balance between absorbed sunlight and emitted LWIR; a similar process goes on for all satellites.

In addition, any equipment on a satellite that uses electrical power will dissipate heat, further raising the satellite's temperature. Although modifying the satellite's surface properties can lessen the amount of LWIR power radiated at a given wavelength, doing so would also increase the object's reflectivity at those wavelengths.[21] Emission and reflection cannot be minimized simultaneously, and lessening one will increase the other.

As stated above, the Earth itself is a powerful LWIR emitter. It will be hard for LWIR surveillance sensors to pick out satellites when seen against this background. Therefore, space-based LWIR surveillance systems will look away from the Earth, spotting objects against the cold background of space. Low-orbiting satellites can only be detected from space by looking just over the Earth's horizon.

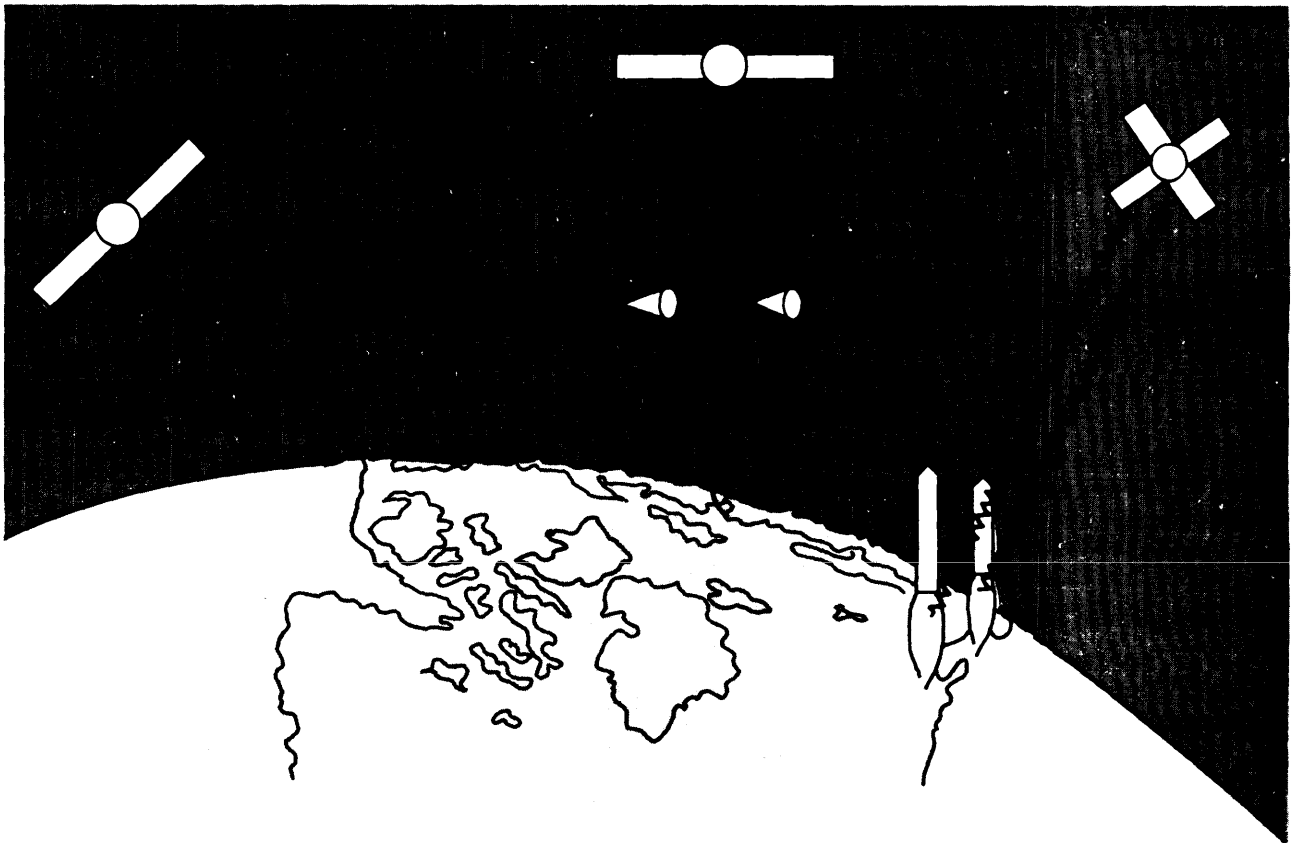
'The PBV itself intermittently fires small rocket motors to maneuver. These rockets emit detectable short- and medium-wavelength infrared radiation, but only when firing. Their radiation is not nearly as bright as that produced by boosters.

20Putting such sensors in space systems requires long-lived (at least several years), lightweight, and low-power cryogenic refrigerators capable of keeping them at their operating temperature.

21A highly reflective surface only absorbs a small fraction of the power striking it. However, since the ability of an object to emit power at a given wavelength is directly proportional to how well it can absorb that wavelength, a reflective object does not emit well, either.

A piece of metal left out in the sun will heat up, even though it is highly reflective, because it radiates even less power in the infrared than it absorbs in sunlight. The infrared power emitted by an object increases rapidly as the object gets hotter (doubling the temperature above absolute zero increases emitted power by a factor of 16), so the metal heats up until it can radiate away as much power as it absorbs.

F gu e 3 ong and Sho Wa e n a ed De ec on



SOURCE Off Ice of Technology Assessment

Another problem may arise from the infrared backgrounds generated by nuclear explosions in the upper atmosphere. Such effects are only partially understood and may remain mysterious in the absence of experimental nuclear tests in the atmosphere. These would, of course, violate the Limited Test Ban Treaty. However, tests involving other sources of ionization are being carried out, in conjunction with computer simulations, to provide more extensive knowledge on what might happen in the upper atmosphere under such conditions.

Other techniques are available to do space surveillance. The U.S. Air Force at present uses both radar and optical observations to monitor objects in space from the ground. Due to interference from the atmosphere, LWIR sensors cannot be used efficiently on the ground. Airborne observations are, however, feasible.

Terminal Phase.–Reentry vehicles and decoys which survive the defenses long enough to reenter the atmosphere enter the terminal phase of a BMD system. Since reentry vehicles can be salvage-fused to detonate if they are attacked, interception must take place at a high enough altitude if “soft” targets below are not to be destroyed.[22] Surveillance systems

‘This “keep-out distance” depends on the yield of the weapon and the hardness of the target. At sea level, a 1 megaton weapon will produce overpressure of 2 pounds per square inch, which structures might survive with repairable damage, at a distance of 13 km (8 miles) from the blast.

that could operate in the terminal phase include ground-based radars and airborne optical and infrared detectors. LWIR detectors, located on airplanes to provide mobility and to minimize atmospheric interference, can detect reentry vehicles which have not yet started to reenter the atmosphere, helping exoatmospheric interceptors to destroy them. Once the RVs have begun reentry, they heat up and start to glow, permitting shorter wavelength infrared and visible detection for endoatmospheric interception.

Issues.–The technology of SWIR and MWIR sensors is fairly mature. Additional software and on-board processing capability will have to be developed to do image processing. The requirements for surveillance and acquisition sensors and processing are not anticipated to stress the state of the art as much as other required BMD technologies will.

LWIR technology is not as far advanced as shorter wavelength sensor technology. As wavelength requirements increase, the task becomes more difficult since new detector materials must be developed and since the systems must operate at temperatures near absolute zero, However, LWIR space surveillance systems have been designed, and the technologies involved have been under investigation for a number of years. The data processing requirements of post-boost and midcourse phase surveillance sensors are also stressing but may not present major technical problems if computer science continues to progress over the next two decades at the same rapid rate which has been evident so far.

Radar technology of the sort applicable for terminal defense is well advanced; radars have been investigated for decades. Of particular interest is making such radars small and cheap, so that they can be proliferated (deployed in large number) to deny the offense the ability to blind the terminal defense by destroying a single, high-value radar. The wavelength at which radars can operate has decreased steadily as technology has progressed. More recently, advances in infrared technology have steadily increased the accessible infrared wavelengths. At present, the wavelength bands for which the two technologies can be utilized are starting to overlap, at wavelengths on the order of a millimeter.

Surveillance and acquisition sensors also have wide application beyond BMD. Space surveillance systems would be useful either to verify an anti-satellite arms control agreement, should one be concluded, or to support an ASAT weapon system, should such an agreement not be entered into.[23] Such systems also may have potential for permitting surveillance of terrestrial targets such as airplanes, but they would need to contend with the highly significant additional problem of distinguishing the target from its surroundings.

High-Resolution Sensors

Surveillance sensors are clearly necessary. However, in most cases they will not be sufficient. In addition to finding suspicious objects, a defensive system must also determine whether they are threatening or benign, aim weapons at the dangerous ones, and determine whether they have been destroyed. These functions of discrimination, pointing and tracking, and kill assessment, respectively, will require additiona-1, higher-resolution sensors. The computational capability which can be built into these high-resolution systems could make it possible to extract useful information from the weak and/or noisy signals which they will be detecting.

Discrimination.—Each layer of a defensive system must be able to differentiate between objects which are missiles or warheads and objects which are decoys designed to fool the defense into treating them as if they were missiles or warheads. If the defense is unable to distinguish between the two, its job is orders of magnitude more difficult.

If the defense is to be able to discriminate effectively, it must utilize multiple phenomenology—repeated observations of the same ob-

[23] See U.S. Congress, Office of Technology Assessment, *Anti-satellite Weapons, Countermeasures, and Arms Control*, OTA-ISC-281 (Washington, DC: U.S. Government Printing Office, September 1985), the companion report to the present volume, for a detailed discussion.

jects using different sensor systems and different physical principles–and it very likely will need high resolution sensors. Although decoys which duplicate one particular observable (radar cross section, temperature, size, etc.) of an actual warhead can be made relatively easily, it becomes progressively harder and harder to mimic more and more characteristics simultaneously. If enough parameters are to be duplicated, in principle it will cost as much to build a highly accurate decoy as it would just to add another RV.[24] Note, however, that the process of making decoys look more and more like warheads, or simulation, may not be as effective as making warheads look more and more like decoys, or anti-simulation. These techniques will be discussed further in "Countermeasures," below (p. 170 ff.).

It is possible, in principle, to decoy ICBM boosters. Discriminating true ICBMs from decoys could be done if accurate data on the origin, trajectory, and characteristics of each launch could be obtained by the boost-phase surveillance sensors. These operations require primarily data processing capability and would not necessarily require high resolution. The effort needed by the offense to defeat such a discrimination scheme would depend on how much data the defense were able to collect on each launch (and on how well the offense knew what the defense was looking at). Note that if a booster decoy were launched from a pad which did not have some of the characteristics of an ICBM launchpad, real missiles might then be placed on similar pads to guarantee them a free ride through at least the first defensive layer. This is an example of anti-simulation.

If ICBMs are able to penetrate the boost-phase system, each can begin to deploy tens of warheads and/or hundreds of decoys. The remaining layers, then, may have to contend with thousands of warheads and hundreds of thousands of decoys and other pieces of debris.

The defensive task is lessened if it is able to maintain "birth-to-death" tracking of all objects. On the one hand, the independence of the different layers will be compromised if later layers rely completely on the earlier ones to detect and discriminate warheads. However, if earlier observations are used to enhance later ones, instead of to replace them, independent observations of the same object can be compared.

One technique which might make discrimination easier would be direct observation of objects as they are deployed off of the PBVs. In principle, it might be possible to see balloon decoys being inflated or to notice some characteristic PBV behavior which indicates that a weapon, rather than a decoy, has just been deployed. Objects correctly determined at deployment to be decoys could therefore safely be neglected by later layers.

Imaging the RVs and decoys requires high resolution. However, the same diffraction phenomenon that limits how tightly a laser beam can be focused also limits the the angular resolution with which images can be resolved. Examining an object with 30 cm resolution (about 1 foot) from 3,000 km away requires an angular resolution of 0.1 microradian. To attain such resolution in the long-wave infrared wavelengths (about 10 microns) which are emitted by such objects, a telescope 120 meters in diameter would be required!

One way to mitigate the diffraction problem is to utilize prior information about the target. If the target's true appearance is already known, and only its precise location is required, the additional knowledge about its appearance makes it possible to calculate diffraction effects and remove them from the sensor image. This process could yield a more precise location than would be otherwise obtainable. On the other hand, if it is not known what the target looks like, as would be the case before it had been identified, this technique would not be applicable.

The only other way to minimize diffraction is go to shorter wavelengths. Reducing the wavelength in the above example by a factor of 50, changing the 10 micron wavelength long-wavelength infrared radiation to 0.2 mi-

[24] It is assumed in this example that adding RVs to defeat the defensive system is prohibitively expensive. If not, the offense presumably would have done just that and would not have worried about decoys in the first place.

cron ultraviolet radiation, permits the same resolution to be obtainable from a mirror 50 times smaller in diameter. However, since the objects to be observed do not emit brightly at these shorter wavelengths, an active system—one which illuminates the target-must be used. A laser radar, or ladar, lights up the target with a low power visible or ultraviolet laser beam while a telescope observes the reflected light. If the laser beam scans sequentially over the telescope's field of view, the laser need not illuminate that entire field at once, minimizing the required power. The wider the ladar's field of view, the less precisely it needs to know where to start looking for a target.

Under certain conditions, antennas which are physically small can have the effect of very large ones, providing high resolution at long wavelengths. Microwave wavelengths on the order of a centimeter, a thousand times longer than LWIR, would require an antenna equivalent to one 120 km long to achieve the 0.1 microradian resolution discussed above! However, very long antennas can be synthesized, in effect, if the antenna is moving. Processing together the echoes of signals emitted at different positions along the antenna's path can yield a resolution equivalent to that of a stationary antenna which is as long as the path of the moving one. Such synthetic aperture radars (SARs), when based on satellites typically moving at velocities of about 8 km/see, might be applicable in high resolution imaging systems. A similar technique for achieving high resolution takes advantage of motion of the target, rather than of the antenna. Such inverse synthetic aperture radars (ISARs) can examine objects which are rotating or tumbling, although they cannot obtain optimal resolution on objects which are vibrating or otherwise arranged to shake.

The price paid for the higher resolution of active sensors is that they cannot operate without revealing themselves, thus warning the offense and giving it an opportunity to spoof, blind, or otherwise interfere with the sensors. To help prevent this, again at the cost of increasing complexity, the defense can separate the transmitter from the receiver(s). In a multistatic system, the receivers would be passive and might be able to operate without revealing their location. The transmitter, of course, would be highly visible, and the targets might still be able to know when they are under observation. However, their ability to interfere with the observations might be complicated if they did not know where the individual receivers were.

Pointing and Tracking.–Once the targets have been detected and identified, weapons must be trained upon them and fired. Pointing and tracking requirements, of course, will differ for each type of weapon. Kinetic-kill vehicles having the ability to home in on their targets need only be pointed closely enough for their on-board sensors to acquire the target. On the other hand, laser beams (except those which kill in one pulse) must be held on a single spot on the target until damage is achieved. Depending on the laser, this can require localizing a beam to the order of tens of centimeters at distances of up to thousands of kilometers, or angular resolutions of less than tenths of microradians. To obtain this resolution in the presence of diffraction, either shorter wavelength active sensors or detailed knowledge of the target itself (or both) would be required.

Part of the pointing problem is determining how far off the beam is if it misses the target. Although by far the majority of a high-quality laser beam's energy will fall within a well-defined central area, there will be radiation outside that main part. Even if the main beam does not strike the target, there will still very likely be enough radiation reflecting off the target for the pointing and tracking sensor to see and use to direct the main beam to the target.[26]

“Even though a laser beam travels at the speed of light (it is light), that speed is not infinite and the laser must be aimed ahead of where the object actually is at the time the laser fires. For a target 3000 km away, the target will have moved between 50 and 100 meters (depending on its velocity) in the 0.01 second that it will take the beam to reach it. Since the laser sees the target by observing light which took another 0.01 second to arrive at the laser, the target's actual position at the time the laser is fired is another 50 to 100 meters ahead of where it appears to be at that time.

It is harder to determine the position of a neutral particle beam in the vicinity of a target. The angle at which the beam leaves the weapon can be measured by probing the beam with a weak laser tuned near a frequency which will be easily absorbed by some of the hydrogen atoms in the neutral particle beam. How well the laser will be absorbed depends on its exact wavelength as seen by the beam atoms, which in turn depends on the particle beam's velocity and its angle with respect to the laser beam.

However, since the effects of a neutral particle beam on a target are for the most part less visible than the effects of a laser beam (the target will not reflect beam atoms back to a sensor which can see them directly, for example), putting the beam precisely on target may be more difficult than it would be for a laser. (Kill assessment for a neutral particle beam in the functional kill mode is correspondingly more difficult; see below.) The problem is lessened, however, since a neutral particle beam will likely be wider than a laser beam and therefore will not need to be so accurately pointed. A possible method of detecting whether the beam has struck the target would be to look for secondary radiation emitted from the target object. This possibility is being investigated.

Homing kinetic-kill vehicles are the most straightforward; they keep the target continuously in sight, correcting their course until impact. The sensors aboard these vehicles can be passive, detecting radiation from the target; active, illuminating their targets and detecting the reflected light; or semi-active, in which the vehicles would home in on reflected radiation which was originally beamed at the target by another source. These sensors would have difficulty in distinguishing between close-spaced objects, as for example in the case of several balloons tethered to an RV at a distance of a few meters.

Kill Assessment.– Determining whether or not a target has been destroyed depends on the type of weapon and on the defensive phase. An ICBM killed in boost phase will either explode or veer visibly off course, being easily detectable in either case. Kinetic kills in midcourse, whereby a projectile hits a target with a closing speed of several kilometers per second, will also be easily seen. However, since many pieces of what had been the target will continue along in more or less the original target trajectory, the battle management system must keep track of all fragments large enough to confuse subsequent sensors and weapons.

The visibility of laser kills in midcourse depends greatly on how badly the target has been damaged. If the target flies apart, its destruction will be easily discernible. However, damage which might not be easily visible may nevertheless disrupt the RVs heat shield so badly that it will not survive reentry. Such an RV, not recorded as killed, may draw additional fire from later layers even though it no longer poses a threat. Further, RVs which appear to fly apart could be merely programmed to jettison parts under attack, even though they may not be killed. This is analogous to submarines releasing oil to make attackers think they have succeeded.

Neutral particle beams used in the functional ("soft") kill mode may present the most difficult problems for kill assessment. Since neutral particle beams (NPBs) penetrate into their targets rather than depositing all their energy on the surface, damage can be done to the interior which may not be visible from the outside at all. Successful NPB attacks in the boost and post-boost phases might cause boosters or PBVs to act erratically and possibly to destroy themselves. However, the case of RVs is different. There is now no guidance on RVs, so the accuracy of an RV would be unaffected by a "soft"- kill. Although the detonation mechanism could be damaged, RVs which have been *successfully* disabled in midcourse might not be distinguishable from live ones. An RV incorrectly assessed as live might waste resources as later layers kill it over again, and an RV incorrectly assessed as dead will do a great deal of damage if it is allowed to pass through later stages to detonate on target. Therefore, to attack RVs with NPBs, the hard kill mode, which would provide visible evidence of destruction, would be required. The use of NPBs in a high current, hard kill mode is being investigated.

Issues.—The discrimination problem is one of the most challenging technical tasks required of a ballistic missile defense. Even if some successful techniques are developed, they will remain successful only so long as the offense does not counter them by developing decoys which are not susceptible to them.

The techniques for high-resolution sensing described in this section are not so far developed as the surveillance and acquisition sensors described earlier. They are extremely computation-intensive and will depend on substantial advances in real-time processing capability.

Pointing and tracking systems capable of operating in a BMD system, particularly in the presence of a hostile enemy, have never been built. Systems having some of the required characteristics, however, do exist today. NASA's Space Telescope, utilizing a technology level which represented the state-of-the-art characteristic of the time its design was finalized, will be able to lock onto a point target with an accuracy of less than 0.05 microradians-on the order of hitting the "S" in a San Francisco stop sign from Washington.

Developing the required kill assessment techniques may be even more challenging. Not much effort has been devoted to this area until recently. Before much progress can be made in assessing whether an object has been destroyed by a given weapon, a better understanding of that particular kill mechanism may be required.

The pointing ability of candidate weapons systems, and the ability of sensors to assess their effects, will likely influence a decision on the ultimate feasibility of those weapons as much as the technical progress made on the weapons themselves.

High-Speed Processing

Many of the systems described above require extensive computational capability. Some of these computations, such as those required for synthetic-aperture radars, will be ones we already know how to do, except they will need to be done faster. Others, such as those required for interpreting images and making decisions based on those interpretations (e.g., "the first twelve objects in this field of view are decoys") will require development of new mathematical techniques and new processing concepts, in addition to high-speed processors. Advances in both hardware and software will be required; they are discussed both immediately below and in that portion of the "System Architecture" section concerning Battle Management (p. 188 ff.).

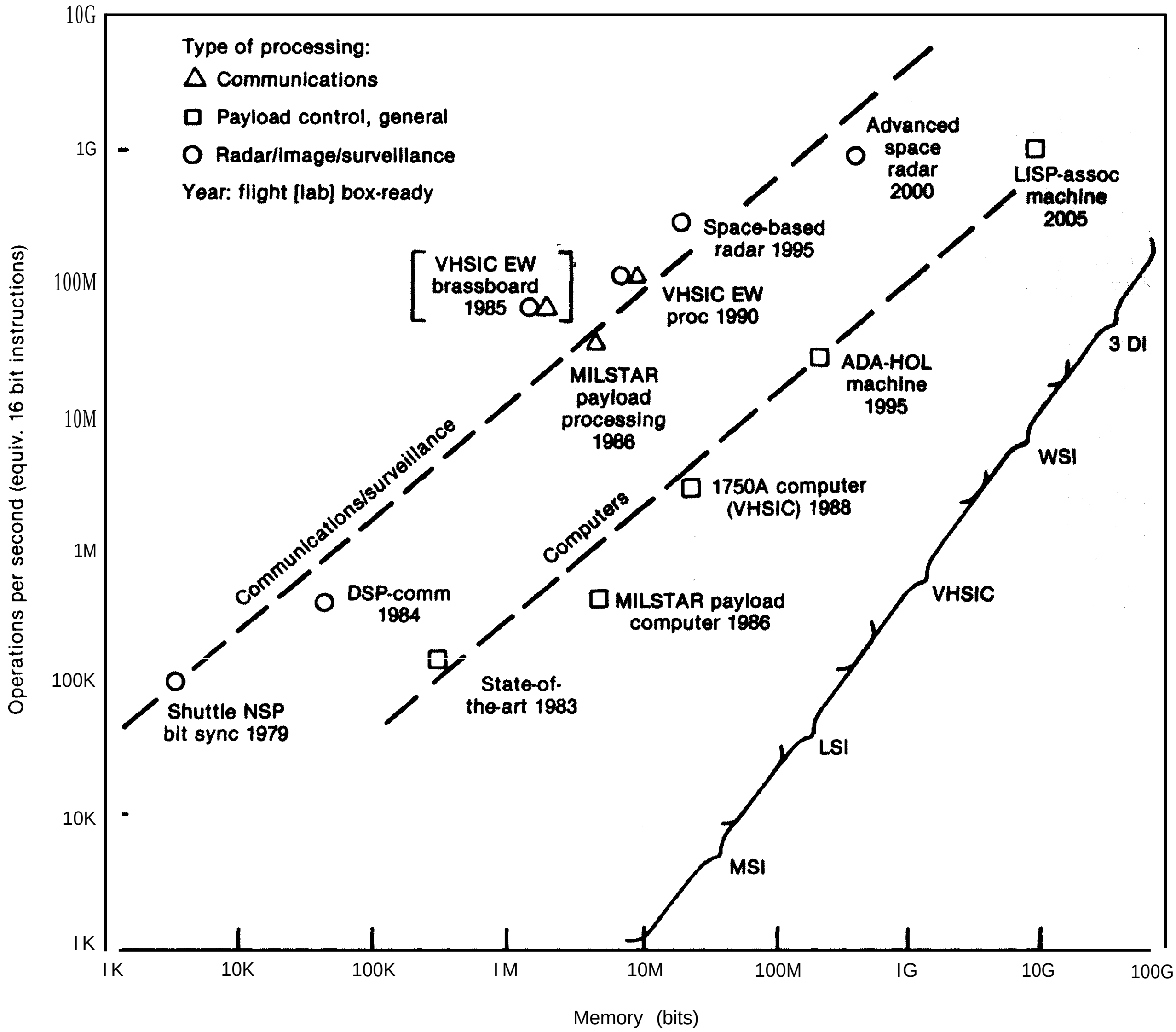
Hardware:

Description. –Data processing technology has steadily evolved at a rapid rate (figure 7-4). Although we have not reached the end of this technological evolution, we are now approaching some physical (rather than technological) limits. Processing speed is limited both by the rate at which individual computations can be done, and by the time it takes the intermediate results to move throughout the processor. The former can be improved somewhat by utilizing higher speed materials and circuit elements, but the latter is limited by the speed of light. Shrinking the overall size of circuits by moving their elements closer together mitigates that problem to some extent, but we are also approaching physical limits on miniaturization of components. Both these approaches are under investigation in DOD's Very High Speed Integrated Circuit (VHSIC) program.

When individual processors approach fundamental limits to their speed, further improvements in processing capability can be made by tying many processors together and doing many calculations at once. Such parallel processing is most effective for problems which lend themselves readily to being broken down into many independent pieces. There is considerable interest in developing parallel processors, and perhaps even more in inventing techniques to utilize these processors efficiently for a wide range of applications.

Another technique for very high-speed signal processing is the use of analog devices. In

Figure 7-4.—Onboard Signal Processing



The past and projected future development of speed and memory size capabilities in signal processing, including on board satellite processors.

SOURCE: TRW

such a device, the data to be processed are not represented as a stream of numbers, as they would be in a digital processor, but rather are represented directly by some physical quantity such as the intensity of part of a laser beam. Certain manipulations of that physical system (e.g., shining that laser beam through a pinhole) are equivalent to performing calculations on the data which that physical sys-tern represents.

To give an example, a digital processor would determine the time required for a ball to fall a certain distance by solving the equations of motion for an object in a gravitational field and calculating the answer. A very simple analog approach to that problem would be to drop a ball and time it.

In this example, the computer would calculate the ball's trajectory much more rapidly than the ball could fall. However, for some specific applications, an analog calculation can be much faster than the corresponding digital one, with the greater speed usually coming at the expense of accuracy. When the calculation is amenable to analog techniques, and when great precision is not required, analog processing (called optical processing when the physical system is a light beam) offers tremendous speed advantages.

Issues.–Although hardware requirements for BMD processing will require technical advances beyond the present state of the art, no technological barrier yet identified appears likely to preclude development of sufficiently capable processors to do those tasks that a BMD system would need to do. In addition to operating rapidly enough, BMD processors will have to be able to operate in an environment where many nuclear weapons could be detonating in space. These bursts produce high levels of charged particles and other radiation which will severely disrupt the operation of circuits which are not radiation-hardened. Use of gallium arsenide (GaAs) instead of silicon holds out promise for making circuits which are both fast and radiation-hard, although these circuits would not be as small as more radiation-sensitive ones.

Reliability is also a key criterion for space system hardware. There is considerable interest in developing fault-tolerant processors which are able to detect and compensate for failures without significantly degrading system performance. The Department of Defense is actively investigating both radiation-hardened and fault-tolerant devices.

Software:

Description. –The task of programming a BMD system will be extremely challenging. Part of this task is developing and implementing specific algorithms which will be needed by individual components of a BMD system. Some of these tasks, such as those involving image processing, will require significant development. In several cases, full utilization of hardware advances (such as parallel processors) will be contingent upon equivalent advances in software techniques.

Other software development tasks involve not so much the implementation of specific tasks but rather the coordination and integration of the different tasks done by various components. These battle management issues are complicated by the sheer size of the job, the number of different contingencies which must be anticipated, and the inability to debug the programs under realistic conditions so that they can be relied upon to function adequately the first time.

issues.–The issues involved in developing and testing BMD software are discussed primarily in the section on "Battle Managemerit, " p. 188 ff.

Power and Logistics

The details of the problems associated with the placement, supply, and upkeep of a space-based missile defense system depend largely on the details of the system to be employed. Here, we shall only outline the problems and the requirements for various of the possible technological options mentioned above. In no way should this outline be considered a complete treatment of the problems which must be dealt with, although the requirements listed should be considered a bare minimum for the successful deployment of a usable system.

Space Power

Description. –Large amounts of power will be required for each battle station, particularly if particle beams, electromagnetic railguns, or free-electron lasers are used. The demand for power may be on the order of tens of megawatts or more. For comparison, this power demand is roughly equivalent to that of a town with a population of at least a few thousands. For some projected applications, large quantities of power must be delivered in short surges.

Past space-based power supplies have ranged from a few watts to several kilowatts. The SP-1OO project, representing an intermediate stage of development for high power space-based systems, is intended to develop a nuclear reactor of 100 kilowatts or more. In general, solar power may not be practical for demands in excess of tens of kilowatts, or for large surge requirements. Possibly, one power technology, most likely nuclear, would be used for the continuous source, and another method, perhaps stored chemical energy, could be used for the surges.

Issues.–The requirements for multimegawatt power systems in space pose engineering problems which are difficult, but within the limits of foreseeable technology. Requiring large surges would provide additional problems for power conditioning.

Minimizing the frequency of maintenance problems is also a serious issue, and one which could become dominant in developing the appropriate power supplies and conditioning. Extremely high reliability would have to be attained, considering the need for many battle stations. The Fletcher Panel wrote of requirements for a 10-year maintenance-free reliability standard for space-based computer and software systems. Placing similar demands on power sources would be a difficult problem. Since such high reliability is not cost-effective for Earth-based applications, where maintenance can readily be performed, it has not yet been developed and there is little experience to draw on. There are no obvious reasons why such reliability would be impossible, although new testing procedures may have to be developed.

Photo credit General ***Electric Co.***

SP-1OO Space Power Nuclear Reactor: Artist's concept of a deployed nuclear-powered electric generator in space. Power levels are designed to be in the neighborhood of 100 kW. The reactor is at the lower left of the drawing. Fingers pointing backwards from the reactor are heat radiators.

Space Logistics

Description.–Whichever weapons options may eventually be chosen, an enormous amount of mass will have to be placed in Earth orbit. Placing objects in geosynchronous orbit, of course, is more expensive than putting them in lower orbits. The Fletcher Panel declared the necessity for a new heavy-lift launch vehicle for space-based platforms of up to 100 metric tons. The space shuttle has a capacity of up to 30 metric tons for orbits of 200 km altitude or so, and less than this at higher altitudes. Additionally, there will be a need for a space transport which can travel between orbits. This would provide means of moving personnel and objects from a space station base to individual system components for the purposes of maintenance and testing. Some deployments might also require such a vehicle.

The mirrors in a laser-based system, as an example, would have to be checked periodically for operability. This would involve removing protective covers and testing the mirrors' performance with lasers. After testing, some maintenance might be required. Other weapon components would also have to be periodically tested and maintained, as would the computer hardware and software.

Altogether, the cost and effort of a space-based system does not end with deployment. Even in the absence of hostile action, there will have to be constant activity in space, occasionally with human presence, to maintain a working system. The threat of attacks on the system would require the erection and maintenance of defenses. It is also possible that vehicles used for deployment may have to have the capability of defending themselves. Alternatively, they would have to be defended by specifically designed protective satellites already in space. A significant fraction of the total payload to be launched from Earth in the early stages could be shielding. Further into the future, it is possible that near-Earth asteroids could be mined for shielding, reducing the requirements for lifting payloads from the surface of the Earth.

Issues.—The feasibility of developing some high-reliability multi-megawatt power system in time for the deployment of space-based BMD assets needs to be demonstrated. Power conditioning for burst mode operation must also be shown to be feasible if such surges are required by the chosen weapons option. The total cost of placing various possible systems in orbit will have to be estimated. For this, it will be necessary to estimate the cost per space platform and the needed constellation size. In addition, the feasibility and estimated cost for component testing, maintenance, and repair must be determined for each candidate system. Finally, estimates will have to be made of the level, cost, and feasibility of self-defense needed for a space-based system. For further discussion of testing and reliability issues, see the section on "Testing, Reliability, and Security," p. 190 ff.

COUNTERMEASURES

Countermeasures to Sensors and Discrimination

Blinding

Sensors used in ballistic missile defense rely primarily on electromagnetic radiation of diverse frequencies. Short-wave infrared radiation emanating from the booster exhaust plumes is used in the boost phase. Post-boost-phase interception will rely on more sensitive infrared detection at longer wavelengths, since the target will not be as hot and its emissions will be less intense. There is also the possibility of using radar or ladar (a technique which uses laser light in a way analogous to radar) to locate targets in the boost, post-boost, and midcourse phases. In the terminal phase, infrared, visible, and microwave wavelengths would be used to locate targets and to discriminate between decoys and real RVs. In addition, communication links could function at various radio, microwave, and possibly optical frequencies.

A generic problem with sensors is the fact that they must be very sensitive in order to perform their tasks of locating and tracking objects, often small ones, at distances of thousands of kilometers. At the same time, they must be able to resist attempts by the offense to disable or confuse them—an easier offensive task than destroying them outright.

Defensive capabilities can be compromised by neutralizing the abilities of the sensors to perform their tasks. If a sensor can be overloaded with energy, particularly at frequencies to which it is sensitive, it may be disabled. The condition may be permanent-here referred to as "blinding"-or temporary. If temporary, say for a period of seconds or minutes, the phenomenon may be referred to as "dazzling. Blinding or dazzling will be effective if the sensor is thereby unable to give correct position and/or velocity information for its targets to the needed accuracy.

There are a number of ways in which blinding or dazzling may be induced. However, sensors could be hardened against some of these effects by a variety of means.

One possible blinding technique could be the occasional nuclear detonation of an RV by the offense by salvage-fusing when attacked, by active battle management, or by preprogrammed plan. One characteristic of a nuclear explosion is the very intense electromagnetic radiation it produces at all frequencies, from gamma rays down to long wavelength radio waves. Additionally, a nuclear explosion in the upper atmosphere causes ionization glows over a range of infrared wavelengths. These glows may extend for substantial distances and persist for many seconds, possibly masking signals from potential targets.

The intense radiation from a fireball could cause problems for sensors. The first problem is one of overloading or even blinding the detector. This possibility could apply to all types of sensors, from visible and near-visible light detectors to radio and radar devices. Secondly, when the nuclear explosion is not as close, the background signal from the explosion might divert the "attention" of the sensor (depending on how "smart" it was).

However, there can be costs to the offense of employing these tactics. In addition to the chance that defensive sensors may be hardened to resist them, the offense must contend with the risk that detonating nuclear explosions during the midcourse phase could "unmask" its own decoys for a substantial distance around the explosion. There is also the possibility that some of the offense's own assets could be damaged.

Large nuclear explosives would be useful to the offensive forces during the terminal phase. When exploded high in the atmosphere, they would disturb the ionospheric layer, thus causing communication difficulties and making tracking and intercept more difficult for minutes. Exploded above the atmosphere, they would create large electromagnetic pulses, which could destroy electronics which are not adequately hardened and would threaten large power grids and power interconnections with destruction or disablement. Defense battle management and C^3I might be threatened.

Nuclear weapons, judiciously used, could be a simple, brute force way of fooling or disabling some sensors. The offense decides when to use them and how many to use. Its only limitation is to avoid collateral damage to its own hardware.

Spoofing and Hiding

Another method of defeating sensors is the use of misleading signals, or the use of decoys, by the offense. This is commonly called "spoofing. " For example, the characteristics of the rocket plume could be changed so that a homing sensor which compensates for the distance from the plume to the vulnerable parts of the booster would do so incorrectly, sending the weapon into space, rather than into the target. The defense's response to this strategy could be to use the infrared emission from the plume only for the initial target acquisition, and to use ladar to illuminate directly that part of the booster to be attacked. Shielding of the plume has also been discussed, although this would present engineering difficulties if all directions were to be covered.

In the midcourse phase, the key problem defined by the Defensive Technologies Study Team is the difficulty of discriminating between RVs and decoys. It is by no means clear that the possible future methods of discrimination that have been proposed and analyzed by the Fletcher Panel will be successful. Further work, both theoretical and experimental, is necessary before an informed judgment on this point can be made.

An often discussed problem for discrimination would be the possible tactic of using aluminized mylar balloons to surround both RVs and decoys. Balloon-type decoys could be very light, and could be included in payloads in quantities far in excess of 10 per RV. When a balloon is placed around the RV, the warhead is made to resemble a decoy—an example of the concealment technique called anti-simulation. Also, shrouds such as balloons or other configurations may be placed around, but not centered on, the RVs. This would make a kill more difficult for some kinetic-energy weapons, since the position of the RV target inside may not be known with sufficient precision.

A decoy could be given signatures which would closely match real RVs for several sensing methods, a technique known as simulation. There may be from 10 to 100 decoys per RV, causing an immense bookkeeping problem. Up to hundreds of thousands of objects could be involved.

A variety of measures has been suggested to overcome this problem.[e] One possibility would be to observe the deployment of the RVs and decoys with ladar during the post-boost phase, if the offense permitted such observations. The changes in post-boost vehicle velocity upon each deployment could be observed, providing a clue to the mass of the object deployed: RVs will be much more massive than decoys. Another tactic might be to attempt to discriminate between RVs and decoys by observing emission from an object at several electromagnetic wavelengths, and by inferring temperature from the radiated electromagnetic energy spectra. Prolonged observations may be needed to perform discrimination using this technique, since the rate of temperature change would be the discriminant.

Many other possibilities for discriminating between RVs and decoys also exist, as well as countermeasures which would make the discrimination task more difficult. Some discussion of these items is presented in the classified annex to this chapter.

[e]See discussion on "Discrimination," p. 162 ff.

Countermeasures to Weapons

Hardening

Some simple passive countermeasures to laser weapons have been suggested. One involves rotating the booster, so that the laser spot must illuminate a larger area. This would work if the period of rotation of the booster were not much longer than the necessary laser dwell time for a kill, and it would force the offensive laser to be increased in power in order to compensate. Such a countermeasure would not work in defending against a pulsed laser, which would deposit its energy in a time much less than the period of rotation of the booster.

Resistance to continuous-wave (non-pulsed) lasers could be increased by coating boosters with ablative shields which evaporate when heated, protecting the booster underneath. The booster would suffer some loss in throw-weight, but could gain some laser protection.

Post-boost vehicles could be hardened against attack, although the weight penalty could prove serious. The possible degree of attainable hardening is an issue to be investigated. RVs are hardened by design, since they must survive the high temperatures and decelerations of reentry. This does not mean that they are immune to attack, even by lasers, but that the energy required for a kill would be substantially greater than in the case of a booster. Kinetic-energy weapons are the weapons of choice for midcourse and terminal phases. Hardening against such weapons does not seem a feasible option. Particle beams would also be difficult to protect against without a great cost in weight. However, in this case, kill assessment could be a serious problem unless a hard kill mode were used.

Evading—Fast Burn

Another much-discussed countermeasure is the use of fast-burn ICBMs by the Soviet

Union. The current SS-18s burn out in about 300 seconds at an altitude of about 400 km. The boost-phase defense then has nearly 300 seconds to reach each target. If the length of the boost phase were to be reduced by one half (to approximately that of the U.S. MXs), the defense's job would be severely complicated. The Soviets are currently testing their equivalent to the MX, the SS-X-24. If boosters are developed which burn out in the atmosphere (say, at 60 to 80 km) in 50 seconds or so, as the Fletcher Panel asserted is possible, some boost-phase defensive techniques would be seriously compromised, if not rendered unworkable. These are the particle beam, and, probably, the X-ray laser, both of which might not penetrate to the required altitude without losing the ability to kill.

The effectiveness of homing vehicles could also be impaired by fast-burn boosters, which would require the vehicles to enter the atmosphere. Their infrared homing sensors might be blinded by atmospheric heating of the windows through which the sensors must look. Since fast-burn boosters burn out both at a lower altitude and in a shorter time, homing vehicles would also have the problem of traversing a greater distance in less time. These problems could be circumvented to a degree if sufficiently accurate targeting were possible after the burn-out of the booster, and before deployment of the RVs during the post-boost phase. One would have to rely on far more sensitive infrared sensors which were capable of finding their targets against the background of the Earth. The homing technology could be strained by this requirement. Alternatively, command guidance of the homing vehicle could be used, whereby the homing vehicles are steered by commands transmitted from other satellites.

All possible systems would face the enormous problem of dealing with a boost phase lasting only one-sixth to one-half as long as the current base case time of 300 seconds. If a 1 second dwell time were necessary on average for a kill, each satellite involved in the battle would be able to handle 50 to 150 boosters, instead of the 300 that each could have handled in the full 300 seconds. The first effect would be to multiply the requirements for the size of the defense constellation by a factor of between 2 and 6.[27] Additionally, the problems of battle management would be severely exacerbated, with more permutations of tracking, target assignment, and kill assessment to accomplish in a shorter time. Again, cost-exchange arguments will have to resolve the issue of whether the offense finds it cheaper to double its fleet, or the defense finds it cheaper to compensate by increasing its constellation size.

The fast-burn booster would also severely strain the capabilities of pop-up weapons. Since the weapons would be placed on missile submarines several thousand kilometers from the ICBM fields, they would have to travel farther in less time than their quarries. This is because the weapons would have to rise high enough to clear the Earth's curvature before they would have straight line paths to their targets. Even if both hunter and hunted were launched simultaneously (which is clearly not possible), the defensive weapon would have to travel farther in the same period of time. Moreover, weapons unable to penetrate below a certain point in the atmosphere must rise high enough so that not only the target, but also the entire line of sight between the weapon and the target, is above the minimum altitude. These difficulties are mitigated if the pop-up weapons are able to detect and destroy the targets after boost phase is over, without the clear infrared plume signals.

The defense could therefore counter a fast-burn booster by improving post-boost-phase detection and kill. The offense could counter again by deploying the post-boost vehicle in much shorter times than is now the case.

In the terminal phase, there is less than 1 minute available for intercept. Countermeasures in this phase, besides the use of nuclear

[27] For some possible types of constellations. constellation size would grow by a smaller factor than that by which the boost phase were decreased. In those cases, constellation size would grow by less than the factor of 2 to 6. See section on "Constellation Size," pp. 179-186.

weapons mentioned earlier, would include the introduction of maneuverable reentry vehicles (MaRVs). Such warheads would engage in a preset series of zig-zag motions to avoid interceptors which would be unable to match the evasive maneuvers in the time required. Small movable fins or other aerodynamic techniques might be used. Counters to this tactic could involve the use of kill mechanisms (probably nuclear) with larger radii of lethality.

Countermeasures to Overall System Performance

Saturation

There are a number of ways to saturate defense systems. For example, in the terminal phase, a preferential offense could overcome defenses if the defender's object is to protect cities. The aggressor could concentrate many RVs on a few cities. If the defense wishes to protect all its cities, not knowing which of them will be attacked, it is forced to deploy defenses at all of them, resulting in the requirement for significantly more defensive forces. If it were considered acceptable to permit the destruction of some cities, the defensive requirements could be relaxed.

For defensive systems which are substantially less than 100 percent successful, one possible countermeasure is simply to increase the number of warheads. It should be remembered that the Soviet SS-18s probably have a capacity of at least 18 and perhaps 30 warheads each, well beyond the currently tested 10.[28] Therefore, a doubling of Soviet RVs could be relatively inexpensive.

For a 50 percent effective defensive system, a simple response of expanding the SS-18 capacity could restore the previous strategic balance, as far as soft target defenses (which were not "preferential defenses") are concerned. This would be the case unless a significant portion of the defensive capability were in the boost phase, in which case more boosters might have to be added by the offense to overcome the defense. If hardened targets were defended preferentially, some of them could be protected against attacks of many RVs;[29] if the defenses operated randomly, some seven or eight RVs per target would still provide high kill assurance for nearly all of the targets. One possible offensive counter strategy would therefore be to aim RVs at soft targets instead of hardened ones. Should the offense counter the defense by adding warheads, the cost of adding a significant number (although perhaps not enough to regain high confidence of killing preferentially defended targets) is likely to be far less than the cost of deploying a 50 percent effective defense. Moreover, the offensive response would require much less time to implement than the defensive system would.

If a defensive system were 80 percent effective, the needed response by the offense to accomplish the same expected damage on soft targets (again, not defended preferentially) would be to multiply the number of warheads by 5. For preferentially defended hardened targets, it would be more difficult for the offense to assure the same expected level of damage.[30] There will clearly be some point of defensive efficiency where the offense will not find it economical to respond merely by increasing warhead and missile production. An estimate of the cross-over point requires knowledge of the cost of other countermeasures which would be possible, as well as of the defensive system.

Saturation could occur particularly during the midcourse phase, where penalties to the offense are small for producing a large number of decoys. These can be cheap and light. It cannot be emphasized too strongly that the ability to discriminate in this phase is essential to the feasibility of the whole space-based BMD concept. The quality of midcourse discrimination determines the difficulty of constructing credible decoys.

[28] See, e.g. B. W. Bennett, How to *Assess the* Survivability *of U.S. ICBMs* (Santa Monica, CA: Rand Corp., 1980), p. 70; W. J. Perry, *Nuclear Arms-Ethics, Strategy, Politics, J. Woolsey (cd.)* (San Francisco: ICS Press, 1984), p. 90; Strobe Talbott, *Endgame (New* York: Harper & Row, 1980), p. 265.

[29] Even so, preferential defenses can be defeated if the offense is able to determine which warheads did not detonate on target, and is then able to retarget additional warheads on those targets.

[30] See, however, the preceding footnote.

Evading—Circumvention

Circumvention of space-based BMD could take several forms. A heavy reliance on cruise missiles or other air-breathing delivery systems, for example, would force the construction of a parallel air defense system in addition to a space-based missile defense. It is conceivable that some elements of a space-based system would be useful in such a defense, but they would be unlikely to be sufficient. An air defense could possibly be technically feasible, but would not be perfect in defending soft targets, and would be expensive. Full analysis of air defense is beyond the scope of this study.

Depressed trajectory missiles launched from submarines could pose difficulties for BMD systems. If the missiles were launched near U.S. territory, the shortened flight times could significantly strain defensive timelines.

Vehicles could be developed which never leave the atmosphere, but glide immediately after booster cut-off. They would bypass the post-boost and midcourse phases (unless those phases employed atmosphere-penetrating weapons). They might, however, be vulnerable to certain types of boost-phase defense and could be vulnerable to terminal defenses.

The boost phase might be avoided entirely by pre-positioning nuclear weapons in orbit.[31] Such weapons, if permitted to be launched and to remain in space, would bypass all but the terminal layer and perhaps the later part of the midcourse layer of a BMD system. The warning time for nuclear attack would be reduced from the 25 minutes or so of an ICBM flight (or 7 to 10 minutes of an SLBM) down to only a few minutes for reentry. In order to be viable, such weapons would have to be survivable against attack, especially since their emplacement in orbit could be considered an extremely provocative act. Although the missions and technologies of orbiting nuclear weapons for ground attack would be quite different from the mission and technologies of a space-based BMD system, some of the survivability techniques necessary for the latter might be applicable as well to the former.

The introduction of bombs into the United States by suitcases, commercial routes, or diplomatic pouches could be accomplished and, for all we know, may already have been done. Techniques for screening such devices by neutron interrogation and radiation detectors are mature technologies and would be easy to use at designated ports of entry. To cover all possible entry routes, however, including deserted coastlines, forests, and deserts along our borders, would be expensive and impractical.

Suppression

With the exception of pop-up weapon concepts, directed- and kinetic-energy weapon scenarios all postulate a large number of space-based stations, which must function continuously in order to be effective. The assets contained in these satellites maybe high-powered lasers, delicate optical mirrors, a fleet of homing rockets, electromagnetic launchers, or particle accelerators. These assets have varying degrees of sensitivity to disruption when subjected to external attack. They would probably have to be shielded as a defensive measure. Required shielding weights could reach up to many tons for each defensive satellite station. Further in the future, as noted earlier, it may be possible to use material mined from near-Earth asteroids for shielding purposes. This would eliminate the need for putting enormous weights into orbit from the Earth's surface.

Even the best shield, however, would probably be useless against a nearby nuclear detonation (within a few kilometers or so). A serious threat to any set of satellites is therefore the concept of space mines. A salvage-fused space mine could be emplaced, if unopposed, within kill range of any ballistic missile defense satellite. Presumably, this would occur during the deployment period. The mines could already be in orbit when the defensive battle stations were deployed, and could then be

“Any basing of nuclear weapons in space would explicitly violate the outer Space Treaty of 1967, However, there is no reason to suppose that the OST would necessarily be any sturdier than the 1972 ABM Treaty, which would already have been a casualty of any space-based BMD regime, moved into position trailing those stations. The cost of a small nuclear (or conventional) device would likely be much less than that of a defensive satellite station for any system being discussed, so the cost-exchange would appear to favor the offense.

A defense against this tactic might need to rely on previously stationed defender satellites, which would be able to destroy the space mines before they approached within lethal range of their targets. The difficulty is, that these defender satellites could also be space mined: the technology for the mines could be developed in the near term, and there is little reason to suppose that, once the United States began positioning a layer of defender satellites, the Soviet Union would be unable to launch (or redeploy from higher orbit) its mines. The defenders would then have to be able to defend themselves against the mines.

The issue revolves then around the ability of mines (an easier and more accessible technology) to disable the defender satellites (anew technology) as they are being deployed for the first time, at a favorable cost-exchange ratio. They must be able to do this at a stage when there may be far fewer defenders than mines. Another important issue is the willingness of either side to initiate hostilities by attacking a suspected mine in peacetime.

Defense satellites or battle stations could also defend themselves by means of kinetic-kill vehicles (KKVS), attacking whatever objects approached. A reply could then be to exhaust the kill vehicles by means of cheap decoys, and then to send in a real mine for the kill. A counter-reply could be to use cheap KKV decoys.

The number of sensing and battle station satellites would be far less than the number of warheads and decoys. Therefore, a directed-energy technology, even if not very effective against an offensive assault, could be deadly when used by the offense against inadequately hardened defensive space assets, provided they could be found. There is always the possibility that these weapons could be more effective for offenses than for defenses. This is because satellites travel in known and predictable paths, and because beam weapons act nearly instantaneously. An attacker can choose the moment to strike, and can take a very long time to plan the logistics and battle management. Battle management problems for an offensive attack on sensing satellites would be minor compared to those of a defender against a ballistic missile attack, when decisions must be made in only a few seconds. Since the place and time of the attack on satellites would be up to the offense, to a large degree, the offensive forces could possibly even use land-based lasers to kill some satellites. To accomplish this, the offense would have to act when the sensors were exposed, and might only be able to deaden a few satellites in a constellation. However, for an attack to succeed, it maybe sufficient to punch a "hole" in the constellation and to attack through the breach. A robust defensive system architecture would have to be resilient against such an attack.

The defense would have to develop means to hide and disguise its satellites, if possible, and decoys would have to be deployed. The sensing satellites and decoy satellites would have to be proliferated to complicate attacks on them. The extra satellites could be deployed in a dormant mode in different orbits from the active sensing satellites, ready to change orbit and come on-line when needed. Careful study would be needed to determine whether the cost-exchange arguments would favor the offensive or defensive forces in such a scenario.

As OTA's companion report on Anti-Sate]*lite Weapons, Countermeasures,* and *Arms Control* indicates, a number of advanced technologies have the potential to be used in future anti-satellite weapons which could be highly effective against current generations of satellites. Several countermeasures which could make satellites more difficult to attack are also under investigation; presumably, space-based components of a BMD system would employ such countermeasures (cf. p. 186 ff.).

Once an entire defensive constellation has been deployed, attacking parts of it could be rather difficult. A system intended to handle tens of thousands of targets, or more, might be more easily able to handle a few in self-defense. In principle, in the mid- to far-term, it might be possible that ground-based directed energy stations could damage the sensors of space assets. However, if a complete constellation were in place, defensive countermeasures could be taken. These include redundancy, the use of battle assessments by bystander members of the constellation, and counterstrikes by the defense to avoid further damage, as well as maneuvers, decoys, and anti-simulation techniques.

While the system is being deployed, components may be vulnerable. It is quite conceivable that the adversary would try to destroy the first few satellites as they were being placed in orbit. A complete system could require many scores of stations, and deploying it would take a substantial amount of time. Therefore, the opportunity will probably exist to attack when few stations are deployed. This could be accomplished with space mines which could already be in orbit, or by ground-launched missiles, possibly nuclear-tipped.

A defense against this countermeasure would be to have a smaller deployed system already in orbit, which could defend the battle stations, as noted above. Another counter might be to threaten retaliation for any hostile act against the newly deployed stations. A full analysis of such deployment battle scenarios would have to be based on more detailed deployment plans and weapons choices which have not yet been made.

Relationships Between Countermeasures

Offensive countermeasures usually provide some penalty which must be considered in evaluating the interaction of the defense and the offense. Possible countermeasures to one part of a defense system may increase vulnerability to other parts. A few examples might be of some interest:

- The fast-burn rocket avoids several types of defensive weapons, and it puts a severe strain on the defense by reducing the time available to attack and kill boosters and post-boost vehicles before the deployment of RVs and decoys. The throwweight penalty may be relatively small. However, the post-boost vehicle and decoys cannot usefully deploy within the atmosphere, so some period of vulnerability in the post-boost phase cannot be eliminated.
- Offensive responses which modify the timing of launches (for example, which launch all at once to put maximum stress on the defense) can interfere with structured attack plans, which then make the terminal layer more effective.
- Nuclear weapons as suppression or blinding agents could disable one's own space assets during a nuclear engagement, and thus prove harmful to the offense.
- Decoys can imitate RVs better if they contain small thrusters, for example. These would behave more like real RVs upon reentry. However, the thrusters are heavy, and thus a throwweight penalty would be incurred. Simple decoys, such as balloons which mimic the optical properties of an RV, might not also mimic other signatures such as radar cross section. More sophisticated decoys would have to be used which duplicated as many signatures as the defense measured.
- Likewise, hardening of the boosters or any other component by heat-countering ablative coatings may increase survivability against some weapons, but would reduce available throwweight for real warheads.

COUNTER-COUNTERMEASURES

The discussion immediately above, pointing out the costs to the offense of implementing countermeasures, is closely connected with the problem of counter-countermeasures. Possible offensive responses to a defensive system may themselves be countered by modifications to the defense.

Counters to all possible countermeasures do not now exist. Ideas have been suggested for some, but it is far too early to determine whether many have any validity at all. They cannot, however, be ruled out. The "fallacy of the last move, " described in the introduction to this chapter, is just as invalid when used to show that countermeasures will always be found as it is when used to neglect the existence of countermeasures at all.

It is misleading to treat the countermeasure/counter-countermeasure competition as a game in which each side moves in turn. In actuality, a proposed defensive deployment must try to anticipate possible countermeasures before they are made. Defensive counters to obvious offensive responses, such as increasing the number of warheads per booster, proliferating decoys, and attacking space-based assets of the defense, must clearly be available before a decision to deploy the defense is justified in the first place. Similarly, the most effective offensive countermeasures will be the ones which anticipate and frustrate possible defensive reactions.

Some counter-countermeasures can be implemented after deployment has been made. Since neither side can anticipate nor prepare for all possible counters by the other, each side can hope to at least confuse the other by attempting to keep its own moves secret while at the same time trying to discover what its opponent is doing. If one side can successfully keep the other from knowing which of a number of possible approaches it might take, it might be able to force the other side to prepare a number of possible countermeasures while preventing it from implementing any of them.

The eventual outcome of this competition will depend on whose intelligence cycle time is shorter. The defense will win if the interval between the time it discovers that the offense is preparing a particular countermeasure and the time when it can neutralize that countermeasure is less than the time the offense requires to discover that its counter has been defeated, discard it, and prepare another. On the other hand, if the offense can constantly keep the defense one step behind, the offense will win. Note that if the defense is required to be 99 percent effective, the offense need only manage to penetrate the defense with a few per cent of its warheads in order to "defeat" the defense (e.g., to cause the defense to fail in achieving its defensive goals). In general, no clear outcome of the offense-defense competition can be predicted.

Examples of counter-countermeasures have been given already in this chapter. If the defense can develop a method to measure the mass of objects in space, the offense will not be able to use light decoys. If the defense is able to develop extremely effective post-boost and midcourse phase defenses (which would require effective discrimination or else extremely rapid weapons), it would not need to use a boost-phase layer and fast-burn boosters would be less useful. (However, the post-boost phase can also be speeded up, and the duration of midcourse phase can be adjusted somewhat by changing trajectory.) If the offense hopes to overwhelm a defense by executing a massive, simultaneous launch, defensive weapons which operate best when many boosters are available at once will be more effective.

SYSTEM ARCHITECTURE

The building blocks of a strategic defense have to be integrated into a coherent, organized system if they are to constitute a useful defense. The system architecture specifies the design of such a system. It denotes what sorts of components are to be included, how they are to be based, and how they will interact. The system architecture is driven by the objectives of the system and by the effectiveness of each of its parts. Cost and schedule factors also influence the system architecture, as do operational constraints imposed by those who will eventually be asked to manage and maintain any deployed BMD system.

Many of the elements required to specify a BMD system architecture are not available at present, such as a clear specification of system objectives (which must include an estimate of the threat such a system will face) and estimates of the effectiveness of various components. Further off still are estimates of the costs and times at which various levels of capability might be deployed. Extensive research not yet conducted must be undertaken to provide this information. In its absence, this study will review some aspects of a BMD system which any candidate architecture must specify. These are:

- Size: the defensive system must be big enough, taking the expected threat into account, to satisfy its objectives.
- Survivability: the defensive system must be able to survive attacks upon itself.
- Battle Management: various components of the system must accomplish their individual missions and must also interact with the rest of the system. Due to the overall complexity of such a system, the way in which its pieces are to act and interact must be considered at the time the system is designed. Moreover, the defensive system must be able to operate with a minimum of human intervention.

Constellation Size

One factor influencing the total cost of systems utilizing space-based weapons is the number of weapons platforms, or constellation size. This number by itself is no more important than other features of the defense, including the as-yet unknown unit cost of the satellites, their vulnerability to attack, and their resistance to potential countermeasures. Furthermore, weapons platforms are only one of the types of space- and ground-based components that a BMD system would require, and the number of weapons platforms needed might or might not accurately reflect the total system complexity.

Nevertheless, calculations of the number of space-based weapons platforms needed to perform boost-phase intercepts have attracted considerable attention because they provide one way to investigate how variations in the quality of system components, or in the demands put upon them, affect the required quantity of those components.

There is no "correct" constellation size. These calculations can only be done assuming hypothetical defensive capabilities and offensive threats, and different sets of assumptions will lead to different numbers of satellites. However, the way in which constellation size depends on various parameters can be determined. If values for these other parameters are assumed, the corresponding number required of defensive satellites can then be found.

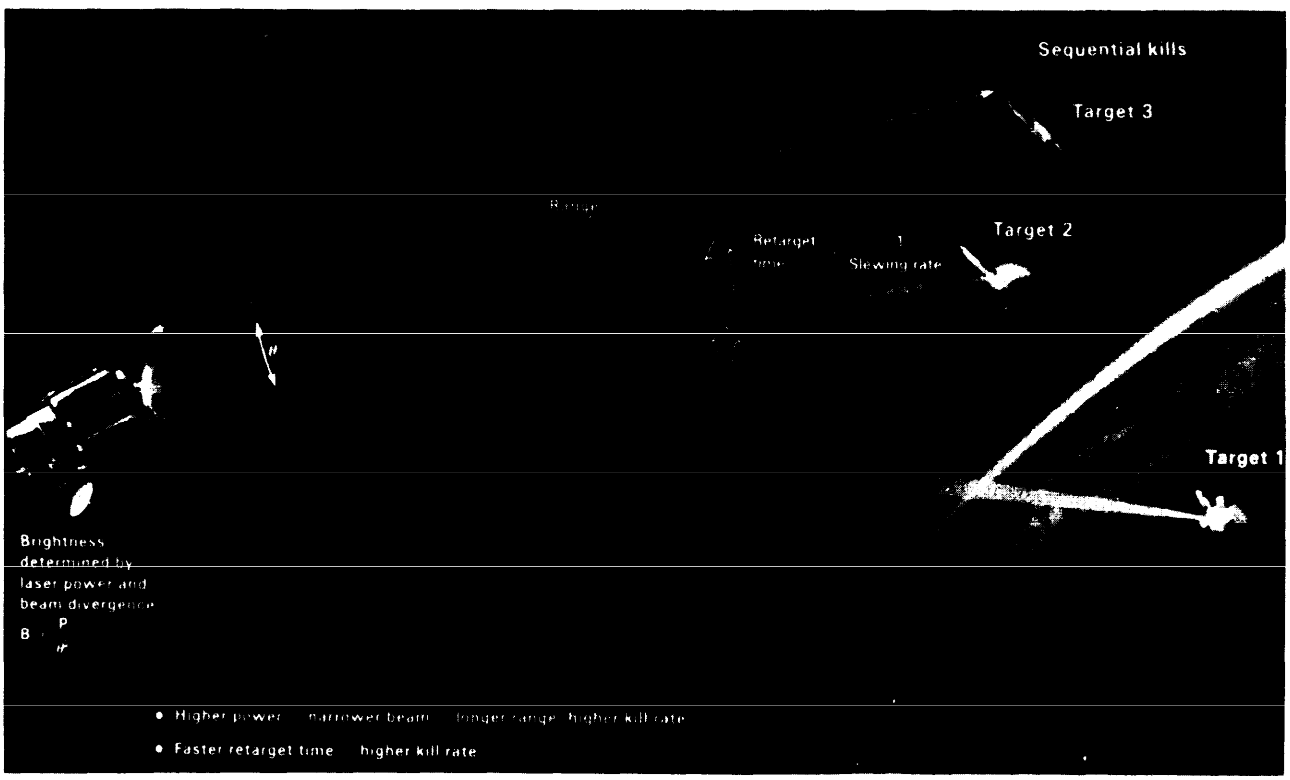
Constellation size depends most directly on the number of missile boosters the defense must handle in a given amount of time. Either increasing the number of missiles or decreasing the available time will serve to increase the rate at which missiles must be destroyed, forcing the defense to grow. Other important factors influencing the size of a defensive constellation are weapon brightness (for directed-energy weapons), retarget or "slew" time, constellation altitude, threat size, and threat distribution. No simple formula relating number of defensive satellites to the offensive launch rate will be valid over the entire ranges of these other factors.

Weapon and Target Characteristics

The effectiveness of a defensive weapon, together with the vulnerability of its target, determines how long (and with what likelihood) it will take the weapon to destroy the target at a given distance. These individual kill times, divided by the total length of time available, determine the number of targets that each defensive weapon can destroy.

Directed-energy weapons are characterized by *brightness*, or how much power they can concentrate into a specified angular range. Since the maximum possible intensity of such a weapon on a target falls off as the square of the distance between the two, the time required to kill a target goes up as the square of that distance. The kill time also depends on the target *hardness-how* much energy per unit area is necessary to destroy it. Although targets may be very sensitive to attack in certain critical spots, target hardness represents the intensity necessary, on average, to destroy the target without taking advantage of these "Achilles heels. "

Kill time, then, is proportional to the target hardness J and the square of its distance R,



g w g g m G
g m m g B g m g
m g g g w g g m
g g g
m g
g g

and inversely proportional to the weapon brightness B. To the kill time must be added the *slew* or *retarget time*, which is the interval required for the weapon to move to the target, stop, and settle down enough to fire:

$$T_{kill} = \frac{J\ R^2}{B} + T_{slew}.$$

To increase the number of targets that can be killed in the available time, a directed-energy weapon must either increase its brightness or decrease its slew time; the more targets each weapon can kill, the fewer weapons are needed. Note that reducing the brightness of a directed-energy weapon by a factor of 2 has exactly the same effect on kill time as doubling the hardness. Both are equivalent to doubling the number of targets (to the extent that slew time is negligible—i.e., if a second target were put next to each existing one and the weapon could switch instantaneously from one to the other).

Kinetic-energy weapons have a different set of characteristics from directed-energy weapons. They can kill only those targets close enough to be reached by projectiles in the available time. Increasing either the projectile velocity or the available time of engagement increases the range of each weapon and lessens the total number required. Hardness is less relevant for kinetic kill; a 1 kg projectile colliding with a booster at a relative speed of 10 km/sec carries the energy equivalent of a heavy tractor-trailer rig traveling at 140 miles per hour.

Altitude

Raising their orbits takes the defensive satellites farther away from the boosters. For directed-energy weapons where the total kill time *is* not dominated by the retarget time, increasing the altitude will significantly decrease each satellite's total kill rate. At the same time, however, satellites in higher orbits can see farther, putting more boosters in their field of view at any given instant. Depending on which effect is more important, increasing the altitude can either increase or decrease the total number of defensive satellites required. (One of the two example constellations presented at the end of this section gets bigger at higher altitudes; the other gets smaller.)

Depending on the target distribution and orientation, an optimum altitude can be calculated to maximize the constellation's kill rate. However, other considerations (e.g., orbital lifetime or satellite survivability) are often more important, so nonoptimal altitudes will in all likelihood have to be used.[32]

Orbit

In addition to altitude, the angle of a satellite's orbit with respect to the Equator (its *inclination angle)* affects how efficiently a satellite can cover a launch site. The satellite orbit most effectively covering a site at a given latitude has an orbital inclination equal to that latitude. For example, a satellite in polar orbit (inclination 90 *o)* will pass over the poles (latitude 90°) on every orbit and can cover high-latitude sites efficiently. However, it will pass over a different portion of the Equator on each orbit as the Earth rotates underneath, and will therefore not often be in a position to cover a particular site at low latitudes. Conversely, a satellite in equatorial orbit passes over every point on the Equator on each orbit, but has no coverage of higher latitudes at all.

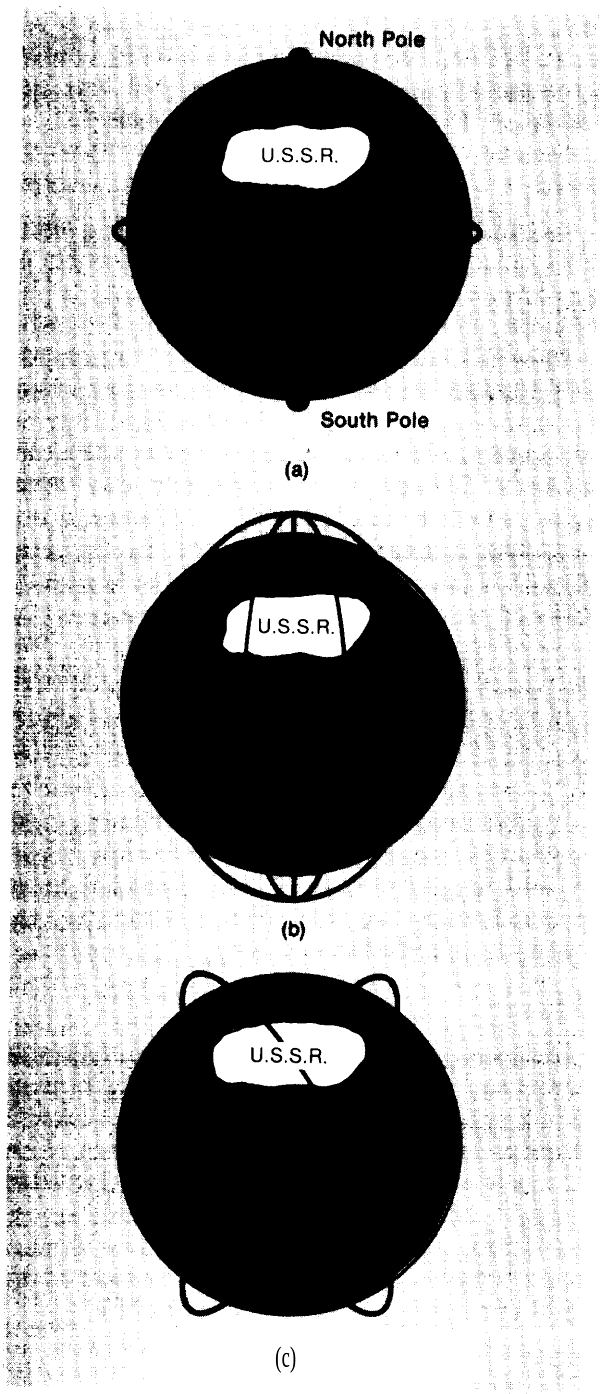
Orbital inclination is not very important for long-range weapons at high altitudes, which are able to attack boosters far from the point on the Earth's surface which is directly beneath the defensive satellite.

Mission

Obviously, a boost-phase system expected to destroy all enemy missiles at launch must be more capable than less ambitious systems which accept some leakage. However, there are more subtle effects of system mission upon system capability. A mission requirement specifying certain orbital inclinations can impose a penalty if those inclinations are not optimal for other mission requirements.

“The chosen altitude must be high enough so that residual atmospheric drag will not cause the orbit to decay too quickly (above about 300 km); survivability considerations might mandate an altitude significantly higher than that (1,000 km or more). The greater altitude would provide increased warning time in event of direct-ascent attack and might lessen the threat posed by other types of ground-based weapons.

Figure 7-5.—Orbital Inclination



Equatorial orbits (a) give no coverage of northern latitudes. Polar orbits (b) concentrate coverage at the north pole. Inclined orbits (c) are more economical,

SOURCE: Ashton B. Carter, ***Directed Energy Missile Defense in Space,*** background paper prepared for the Office of Technology Assessment, OTA-BP-ISC-26, April 1984,

One example would be requiring a boost-phase defense to counter submarine-launched missiles as well as land-based ICBMs. The number of extra satellites to counter SLBMs need not be much more than the number needed only for ICBMs because most of the additional capability (in terms of weapons platforms) needed to counter SLBMs comes “for free. ” In a system sized to handle the existing Soviet land-based ICBMs, only a small percentage of the defensive satellites will be within range of those missile fields at any one time. The rest will be somewhere else. Those others which are over the oceans can counter SLBMs *if they are in a position to see them.* In order to cover possible Arctic Ocean deployment of Soviet SLBMs (which would have to be able to break through the polar ice cap), at least some of the defensive satellites must be in polar orbit. These satellites will be less effective against land-based ICBMs than they would be if they were in less inclined orbits which did not waste time going over the poles.[33]

Target Distribution

In the example immediately above, the capability to handle SLBMs came at almost no cost because SLBM launch areas are far from ICBM silos. Those satellites which would handle the SLBMs in an attack would probably be different from the ones handling the ICBMs, so both jobs could be done simultaneously. Similarly, should the Soviets add additional ICBMs in areas so far away from their exist-

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Since not all the missiles on a sub can be fired at once, and since the subs are more widely dispersed than missile silos, the rate of submarine-based missile launches per unit area of the ocean will be smaller than the corresponding rate of ICBM launches per unit area in a missile field. Therefore, SLBM launches should be easier for a boost-phase defense to handle. This becomes less true for higher altitude constellations, where each satellite defends against launches from a wider area and more satellites are in a position to shoot simultaneously at ICBMs and SLBMs. Moreover, these statements apply for simultaneous SLBM and ICBM launch. Should the Soviets be able to time SLBM launches so that they occur under defensive satellites which have already been depleted in countering ICBMs, the SLBMs would not be intercepted. However, the orbital arrangement of defensive satellites can mitigate this problem to some extent by ensuring that satellite coverage areas overlap.

Midcourse systems will have a harder job defending against SLBMs than against ICBMs, since normal SLBM flight times are shorter than those of ICBMs. SLBMs flying depressed trajectories can arrive on target even faster than those on more usual flight paths.

ing missiles (and from SLBM launch areas) that the defensive satellites needed to counter the increase were not already being used to attack existing boosters, no additional defensive capability would be needed to handle the increase.

However, targets which are close together are more difficult for the defense to handle than targets which are dispersed. Should additional missiles be added near existing ones (or near each other, if there are enough of them), new defensive satellites would have to be added to counter the increase. Boosters located in the same general direction from a defensive weapon can be considered "near each other" if that weapon requires about the same amount of time to target and kill each of them. For directed-energy weapons that operate by "thermal kill, " this will be the case if the kill time for each booster in a group is dominated by retarget time (e.g., the time required for the beam to switch between targets is large compared to the amount of time the beam must dwell on each target) or if the dimensions of the missile field are smaller than the orbital altitude of the weapon. Note especially that missiles within existing ICBM missile fields are already "close together' by these criteria. Deployment in a closely-spaced basing mode such as that proposed for the MX missile ("dense pack") would be *much* closer together than required to be considered near each other.[34]

Examples

In this section, we examine two different hypothetical laser weapon systems. In the first case, the lasers generate **20 MW of power at a wavelength of 2.7 microns; this power is directed with mirrors 10 meters in diameter**. The brightness of these lasers is 2.3×10^{20} watts per steradian (w/sr).[35] Systems having these parameters, or very similar ones, have recently been discussed fairly extensively in the literature.[36]

The second case utilizes extremely bright lasers generating 25 MW of power at a wavelength of 0.25 microns. These lasers have 25-meter diameter mirrors. The greatly reduced wavelength, in particular, yields a very large increase in brightness, since it permits the radiation to be focused to a much smaller spot.[37] An increase in brightness by a factor of 911 over the first case is thus obtained ($B = 2.1 \times 10^{23}$ w/sr).

A booster 4,000 km away could be irradiated with an intensity of 1.5 kw/cm^2 in the first case and 1,300 kw/cm^2 in the second one. If that booster had a hardness of 10 kJ/cm^2, the value taken for these examples, it would be destroyed in 7 seconds (ignoring retarget time) in the first case and in 8 milliseconds (similarly ignoring retarget time) in the second.

These hypothetical cases have been selected only for the purpose of demonstrating how constellation sizes vary as system parameters are changed. The actual parameters chosen do not represent an optimized system design, nor does their use imply that either system could or would be constructed. By way of reference, the first case uses space-based lasers which are much more capable than any existing ground-based ones; the second case requires great advances in optical capability beyond those needed for the first case.

Perfect optics is assumed, so that the beam spreads at the minimum diffraction-limited angle. Absorption by the atmosphere, in particular absorption by the ozone layer which would severely affect the second case, is neglected.

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[34] For satellites at sufficiently high altitudes or having retarget times much longer than required dwell times, missiles anywhere in the Soviet Union would be considered close to each other.

[35] One *steradian*, a measure of *solid angle*, covers that portion of the surface of a sphere having an area equal to the square of the radius of that sphere. (This angular measure is independent of the size of the sphere; all spheres have a total solid angle of 4 π steradians.) Considering a directed-energy weapon to be at the center of a sphere and aimed at some small portion of that sphere's inside surface, the weapon's brightness is given by the amount of power {in watts) the weapon can beam into a given angular range (in steradians). Brightness increases either if power increases or if the width of the beam (the beam's solid angle) decreases.

'For a summary of references, see Richard L. Garwin, "How Many Orbiting Lasers for Boost-Phase Intercept?' Nature, vol. 315, May 23, 1985, p. 286.

[37] Brightness is proportional to the square of the ratio of mirror diameter to wavelength.

For the purposes of this example (unless otherwise noted), Soviet boosters are assumed to have been replaced with hypothetical MX-like boosters having a burn time of 180 seconds and the 10 kJ/cm^2 hardness figure given above. Such boosters would probably be more difficult for the defense to destroy than most existing Soviet boosters, but they also would be much easier to destroy than boosters that the Soviets could develop in the time it took the United States to deploy such a defensive system. In addition, it was assumed that a spot at least 15 cm in diameter would be required to destroy a booster. If the laser was capable of focusing to a smaller spot than that, its beam, in effect, was blurred to be 15 cm wide on target. Only boost-phase engagements are presented here. The effective engagement time is 150 seconds since we assume that the defense requires 30 seconds to identify and assess the attack and to prepare to fire. No limitation was imposed on the resources available (e.g., power and fuel) on each station; the number of kills each satellite could make was limited only by the number of targets in view and the available time.

For most cases, Soviet missiles were assumed to be located at 12 sites having the approximate locations of Soviet ICBM fields. Each hypothetical launch site was given 117 boosters for a total of 1,404, approximating the size of the present Soviet ICBM force. Many cases were also run for a doubled threat where each site had 234 missiles. Defensive satellites were placed in 600 inclined orbits, maximizing their coverage of Soviet missile fields. The lasers were credited with being equally effective against surfaces at any orientation.

Examples were also run for satellites in polar orbits and for a Soviet force concentrated at a single site—the most stressing case for a boost-phase defense. As was mentioned above, a "single site" does not necessarily indicate a high density of boosters. In these examples, distributing all Soviet boosters over an area the size of the State of Ohio effectively puts them in a single site. One run took a more realistic angular dependence for laser lethality which, in effect, made it easier for a laser to kill a missile firing broadside at it than firing straight down on its nose cone.

Some examples, run for both laser brightnesses, assumed that the Soviets would use "fast-bum" boosters which burned out in 80 seconds, rather than 180. A 30 second delay for identification and assessment was taken for these cases, as for the others.

The computer model used was provided by Christopher Cunningham at the Lawrence Livermore National Laboratory. A constellation of defensive satellites is specified by laser brightness, beam divergence (which depends on the ratio of mirror diameter to laser wavelength), altitude, retarget time, number of satellites, and orbital placement. For each set of conditions, the offense was assumed to launch at the moment when the defensive satellites were in the worst position to handle the attack, and the minimum defensive constellation size capable of destroying all the missiles under those circumstances was found. Constellations were not augmented to provide spares to account for satellites which would be out of service due to attack or maintenance. The following two tables present the results of the computer simulations for the two cases.

Observations

The most useful information derivable from the above tables is the relationship showing how minimum constellation size varies with orbital altitude and with retarget time. This variation is less sensitive to individual assumptions than is the actual size of the constellations, which could be increased or decreased by taking different values for other parameters. We draw the following conclusions for the first example:

1. The number of satellites needed in the constellation varies linearly with the threat size. The only exception is for very low altitude constellations (300 km) having retarget times substantially less than 1 second and attacking widely distributed boosters. In this case, the number of satellites increases less rapidly than the number of boosters. Even in this

Table 7-1.—Constellation Size Given Assumptions in Text
20 Megawatt **Laser/10 Meter Mirror/2.7 micron**
Booster Hardness 10 kj/cm^2

Altitude	300 km			
Retarget time	0 sec	0.1 sec	1 sec	3 sec
Threat size:				
1,404	80	88	192	396
2,808	120	143	368	777
Altitude ., ...	1,000 km			
Retarget time ., ...	0 sec	0.1 sec	1 sec	3 sec
Threat size:				
1,404	108 *	117	192	336
2,808	204	224	384	667
● —Base case				
Altitude	3,000 km			
Retarget time	0 sec		1 sec	3 sec
Threat Size:				
1,404	312		357	440
2,808	620			

Excursions about base case (noted with asterisk above):	
Base case (Distributed launch, 1,000 km altitude)	108
Fast burn (80 sec), 1,000 km altitude, O sec slew	3 0 6
Fast burn (80 sec), 1,000 km altitude, 1 sec slew	588
Fast burn (80 sec), 300 km altitude O sec slew	176
"Single site" launch, 1,000 km altitude	180
"Single site" launch, 1,000 km altitude, double threat	352
"Single site" launch, 300 km altitude	132
"Single site" launch, 300 km altitude, doubled threat	234
"Single site launch plus fast burn, 300 km altitude, O sec slew	352

Table 7-2.—Constellation Size Given Assumptions in Text
25 **Megawatt Laser/25 Meter Mirror/O.25 micron**
Booster Hardness 10 kj/cm^2; Atmospheric Absorption Ignored

Altitude	1,000 km			
Retarget time	0 sec	0.1 sec	0.25 sec	1 sec
Threat size:				
1,404	10	15	25	6!3
2,808	14	27	42	128
Altitude	3,000 km			
Retarget time	0 sec	0.1 sec	0.25 sec	1 sec
Threat size:				
1,404	6	9	16	40
2,808	9	16	27	75
Altitude	10,000 km			
Retarget time . .	0 sec	0.1 sec	0.25 sec	1 sec
Threat size:				
1,404	5	8	10	26
2,808 ., ...	9	13	20	49
Altitude	15,000 km			
Retarget time. . . .	0 sec	0.1 sec	0.25 sec	1 sec
Threat size:				
1,404	6	8	11	26
2,808 ., ...	10	14	22	49

"Single site" launch, 3,000 km altitude, O sec slew	.7
"Single site" launch, 3,000 km altitude, O sec slew, double threat	12
"Single site" launch, 15,000 km altitude, O sec slew	7
Fast burn, 3,000 km altitude O sec slew	
Fast burn, 3,000 km altitude, O sec slew double threat	24
"Single site, " fast burn 3,000 km alt , 0 sec slew	16
"Single site, " fast burn, 3,000 km alt , 0 sec slew, double threat	25

case, the constellation size varies nearly linearly with the threat size for a "single site" launch.

2. For the particular parameters chosen for hardness, boost time, etc., the constellation size must be at least 100 satellites for altitudes of 1,000 km and above.
3. Grouping boosters at a "single site" increases constellation size by about 60 percent. If the threat is doubled by placing the additional boosters at a "single site, " the defensive constellation should more than ***double*** (except, possibly, for the low altitude, low retarget time case). By grouping the added boosters together, they become even harder to kill than if boosters were doubled at their existing locations.

For the second (superbright) example, we find the following:

4. The altitude is much less important than the slew time in determining constellation size. The limit on the kill rate appears to be determined by the slew time, which, when longer than 0.25 second, is much longer than the time needed to kill an individual target. The number of targets each satellite can kill is then limited, not by laser brightness, but by the time needed to retarget. In this regime, defensive constellation size scales linearly with threat size.
5. For some of the particular parameters chosen here, constellation sizes can be very small.
6. For retarget times at or below about 0.25 second with distributed launch, the defensive constellation size scales less than ***linearly*** with the threat size. In this regime, however, the difference in absolute number between the actual scaling and linear scaling is not very big.
7. For very high altitude constellations, the entire Soviet Union is effectively a "single site, and constellation size varies essentially ***linearly*** with the threat even for zero retarget time.

Further Notes.–For cases where constellation size increases linearly as threat size increases—most of the ones examined here—the use of fast burn increases the constellation size in inverse proportion to the time of engagement. For the dimmer laser system, putting all the Soviet boosters in one place increases the required constellation size by two-thirds, since fewer defensive satellites are in a position to attack boosters and more are therefore needed. However, depending on their attack plans, the Soviets may not want to "group" their boosters. Although such a grouping would still be large enough that it would not necessarily be any more vulnerable to attack than their existing booster distribution is, the Soviets would lose the ability to conduct certain types of structured (precision-timed) attacks. Because of flight time variations in reaching targets when the launch occurs simultaneously from one limited region, one could not simultaneously strike widely separated targets with a simultaneous launch. For the brighter system, there is less advantage to grouping boosters. The satellites have longer range, and exact booster placement does not matter as much.

Although not shown in the table, placing the defensive satellites in polar orbit increases the constellation size by less than 20 percent over the inclined orbit case for the lesser brightness system. Modeling the laser effectiveness by including the effects of the angle between the laser beam and the booster surface also makes less than 20 percent difference.

The results given in these tables do not apply to kinetic-energy weapons, where the important parameters are the velocity of the driven projectiles, and the rapidity of fire. A separate analysis would be needed to determine the behavior of constellation size in those cases.

Survivability

If the defensive system is itself vulnerable to attack by the offensive force, the offense can penetrate it by diverting part of its resources to attacking the defense directly, permitting the remainder to continue unimpeded. Therefore, such defenses themselves have to be effectively invulnerable to attack. Paul Nitze, chief arms control adviser to President Reagan, stated criteria for BMD which included the requirement that

> The technologies must produce defensive systems that are survivable; if not, the defenses would themselves be tempting targets for a first strike, This would decrease rather than enhance stability. "

General Abrahamson, director of the SDIO, similarly has recognized that

> . . . the key functional components of a defensive system must be made survivable against attack. This problem is particularly keen for defensive space assets."

Some scientists have stated that a defense should not rely on space-based weapons platforms since they would be very difficult to defend. Discussing ballistic missile defense systems with a House subcommittee, Dr. Edward Teller emphasized that

> I am not talking about orbiting space laser battle stations. I am talking about third generation weapons and other instruments that pop up into space when the time to use them has come.[40]

"We need eyes in space, " continued Dr. Teller, but once they are there, "our eyes are sensitive and our eyes are in danger. "

However, other opinions have been quite the opposite. In an interview, Presidential Science Adviser George Keyworth remarked without elaborating that as a result of recent advances, "We possess the technology today to deal very effectively with survivability of space assets."[41] General Abrahamson, with a slightly different emphasis, stressed *functional* surviv-

[38]Speech before the Philadelphia World Affairs Council, Philadelphia, PA, Feb. 20, 1985.

"J. A. Abrahamson, "The Strategic Defense Initiative, " *Defense/84*, August 1984, p. 8.

[40]Defense Department Authorization and Oversight Hearings on H.R. 2287, Research and Development Subcommittee, House Committee on Armed Services, Apr. 28, 1983, H. A.S.C 98-6, Part 5 of 8, p. 1357.

[41] Inter}, iewed in *Science and Government Report* June 1, 1984, p. 5.

ability of space systems rather than *individual* survivability:

> An analogy can be drawn by comparing [satellites] to the evolutionary use of military aircraft during World War 1 . . . The fact that extremely delicate and vulnerable airplanes became legitimate military targets did not end their utility in World War I, nor in any conflict since. Both sides quickly learned how to make their airplanes survivable . . . Although these [survivability measures] did not eliminate an enemy's ability to concentrate forces to destroy a given airplane, *squadrons were so constructed that missions could be accomplished in the face of losses of large numbers of individual airplanes. All these tactics and technologies are applicable to spacecraft survivability* . . .[42]

Nevertheless, ensuring the survivability of space systems or space functions—in the presumed presence of a highly capable enemy BMD system, and in the highly stressing environment of nuclear war-is as challenging a task as it is crucial. After all, many of the technological advances required to destroy ballistic missiles could also be effective against satellites, and in many cases satellites prove much easier to destroy. Satellites in orbit today are more fragile than ballistic missile boosters, which in turn are easier to destroy than reentry vehicles. Satellites of the future need not be so fragile, but hardening them will impose costs and may interfere with their function. Sensor satellites in high orbits may be concealable, at least for a while; concealing battle station satellites in lower orbits would be quite difficult and such satellites would be even more difficult to conceal if they carried extensive shielding.

Furthermore, the presence of orbiting BMD components greatly increases the incentive for the other side to develop highly capable ASATs to negate those components. The defense must constantly maintain full capability to defeat an attack; depending on defensive system design, the offense may need only to "punch a hole" through the defense in order to challenge its effectiveness seriously. The offense can choose both the time and the place of the attack, and might have the advantage of surprise.

Passive and active measures can both be used to improve space system survivability. Some relevant technologies are given below; none are applicable in all cases, and all impose costs and/or are themselves vulnerable to countermeasures. Much more information on these techniques and technologies can be found in chapter 4 of OTA's companion study of *Anti-Satellite Weapons, Countermeasures, and Arms Control. See also* the section earlier (p. 175) on "Suppression" as a countermeasure to BMD.

Passive Measures

- Hiding: Satellites can be made more difficult to detect. For example, they could be miniaturized or stored in a tightly folded configuration and deployed only just before use, or they could be hidden either in very distant orbits or very close ones, where they might be hard to detect against the Earth's background.
- Deception: Satellites can be simulated with decoys or hidden in clouds of aerosols or chaff.
- Maneuvering: Satellites can evade attackers.
- Hardening: Satellites can be made resistant to attack.
- Proliferation: Satellites can be replicated, and damaged satellites can either be replenished with on-orbit spares or reconstituted from the ground.

Active Measures

- Jamming: Satellites can interfere with the sensors of attackers by overwhelming or saturating them.
- Spoofing: They can fool attackers by emitting or broadcasting deceptive signals.
- Counterattack: Highly capable BMD weapons can be trained on attackers; alternatively, armed defensive satellites (DSATs) can be provided to escort and defend other satellites.

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[42] Abrahamson, op. cit., p. 9 (emphasis added).

Secrecy

No matter what combination of active and passive measures is utilized, protecting satellites from a hostile and responsive opponent will be an interactive process. (See section on "Counter-Countermeasures," p. 178.) In a competition where different techniques and measures may suddenly be introduced, it becomes very important for each side to keep its opponent from learning in advance what it is doing. It is equally important to learn as much as possible about what the opponent is doing.

Security therefore becomes especially important in ensuring survivability. However, it will be more important to protect those items which the opponent cannot easily find out for himself, such as battle tactics or the locations of "hidden" satellites, than it will be to protect those things that will become obvious when a system is deployed. That one or another of the techniques under "active measures" or "passive measures" above is intended to be used in a defensive constellation should not be particularly sensitive; exactly how that technique is to be implemented and under what circumstances it is to be used would be.

However, any system that relies solely on keeping some particular piece of information secret has a catastrophic failure mode should that information be revealed.

Survivability-Summary

Overall, the Fletcher Committee concluded that

> Survivability of the system components is a critical issue whose resolution requires a combination of technologies and tactics that remain to be worked out.[43]

From what OTA has been able to determine, examining data on both an unclassified and a classified basis, the "technologies and tactics" required to resolve system survivability issues still "remain to be worked out. " Either the work done so far has been so highly classified that OTA has not been granted access to it, or else it has not materially affected this conclusion. It is likely that Congress would require assurance that those survivability issues have indeed been satisfactorily addressed before agreeing to fund a full-scale development system.

Battle Management

Definition

Battle management is concerned with the allocation of resources. A ballistic missile defense system consists of a number of sensors and weapons, each having a finite amount of available power or fuel. Engagements against attacking ICBMs take place in a region of space and an interval of time determined by geometry, weapon capability, and the attacker's strategy. The defensive components (sensors and weapons) which provide coverage of that region have to do their jobs within the available time. The battle management system—the set of rules specifying the operation of and the relationships between system components, and the computers which process those rules—must ensure that the overall defensive mission is accomplished successfully.

This job is a demanding one. The first major conclusion of the Defensive Technologies Study Team subpanel on Battle Management, Communications, and Data Processing was that:

> Specifying, generating, testing, and maintaining the software for a battle management system will be a task that far exceeds in complexity and difficulty any that has yet been accomplished in the production of civil or military software systems.[44]

[43] *The Strategic Defense Initiative: Defensive Technologies Study* (Washington, DC: Department of Defense, Office of the Under Secretary for Research and Engineering, March 1984), p. 5.

[44] *Battle Management, Communications, and Data Processing*, B. McMillan, Panel Chairman, vol. V of *Report of the Study on Eliminating the Threat Posed by Nuclear Ballistic Missiles*, J. C. Fletcher, Study Chairman (Washington, DC: Department of Defense, Defensive Technologies Study Team, February, 1984), p. 4. This volume will be referred to as the DTST Report, vol. V. Unlike the other six volumes of the DTST report, vol. V is entirely unclassified. Distribution is limited to U.S. Government agencies or as directed by the Assistant for Directed Energy Weapons, OUSDRE/ADE W, The Pentagon, Washington, DC, 20301.

Hardware

Although the hardware required for BMD battle management also exceeds the present state of-the-art, the panel recognized that "the basic technology is evolving rapidly and is likely to be available when needed. "[45] In addition, the panel found that technology exists today to transmit data between system components at the rates which a BMD system would require.

Battle management functions are done both within a given defensive layer and across different layers. Each layer must perform acquisition and tracking, target discrimination and classification, and resource allocation. Across layers, the defensive system must provide overall surveillance, specify rules of engagement, delegate control, coordinate between layers, trade off defending Earth targets against defending itself, and furnish current assessments of the state of the defense system and the battle. This last function includes selecting relevant portions of a much larger set of data and presenting it to the command authority.

Software

The subpanel of the DTST estimated that for the system to monitor 30,000 objects (not a highly conservative number; values of 100,000 and 300,000 were also considered), it would need to maintain a track file of about 6 million bits of information, or about 200 bits per track. This amount of data is about the same as would be contained on 350 double-spaced typed pages, and could be transmitted within a second at the data rates considered by the panel.

The software required, however, was estimated to be three to five times more complex than what was the largest similar existing military software system-that controlling the Safeguard ABM system developed in the late 1960s and early 1970s. That project, constituting just the terminal and late midcourse layers of a BMD system, required over 2 million lines of computer programming, leading the DTST to estimate that over 10 million lines of code might be required for the BMD systems which they investigated. More recent estimates have gone considerably higher.

Such a software system "will be larger, more complex, and have to meet more stringent controls than any software system previously built, "[46] reported the subpanel. No one person will be able to comprehend or oversee the entire system and developing such a system will itself likely require the development of automated programming techniques. Computers will not only be needed to create the final BMD program but will also have to subject it to exhaustive reliability testing. One analyst[47] has expressed the view that, in the absence of "extensive operational testing in realistic environments, " it would be essentially impossible to produce error-free software of the size and complexity required. This argument claims that it would be impossible otherwise to be sure that all catastrophic design flaws had been eliminated, even if automated programming techniques were applied.

Decentralization and Survivability

The data processing requirements for a system of this complexity must be distributed among the system elements. This decentralization serves both to minimize the amount of data which must be passed from component to component as well as to enhance survivability by eliminating indispensable elements. Having a surveillance sensor, for example, process each raw image locally and transmit only the position of a target to a weapon, rather than transmitting the entire sensor field of view, cuts down greatly on the transmitted data rate and lessens the risk that the system could be paralyzed by failure of a central processor. With such a decentralized architecture, the Fletcher subpanel concluded that:

> . . . it appears possible to design a battle management system having a structure that can survive battle damage as well as other parts of the BMD system do.[48]

"Ibid., conclusion 4, p. 6.

"Ibid., p. 45.

"Herbert Lin, "Software for Ballistic Missile Defense, " (Cambridge, MA: MIT Center for International Studies, July 1985).

[48]DTST Report, vol. V, op cit., conclusion 9, p. 9.

Command and Control

Given the short times and the large number of individual tasks which need to be done in a ballistic missile defense engagement, the system must be designed to run as much as possible without human intervention. Command and control of such a system must also be highly reliable. The Fletcher subpanel declared that:

> No BMD system will be acceptable to the leaders and the voters of the United States unless it is widely believed that the system will be safe in peacetime and will operate effectively when needed.[49]

Even if the weapons utilized are incapable of causing mass destruction should they be fired in error, the activation of a defense system (like the placing on alert of strategic nuclear forces today) would almost certainly be noticed by the other side, and could instigate or escalate a dangerous crisis situation. This danger might be mitigated by the adoption of mutual confidence-building measures by the United States and the Soviet Union.

Testing, Reliability, and Security

These last issues of reliable control exist today with respect to strategic offensive nuclear forces. However, the Fletcher subpanel highlighted them because of the "unprecedented complexity" of the BMD mission and because these issues bear directly on the design of the battle management system itself. Another problem existing today, but aggravated in a BMD system, is the inability to test it under realistic circumstances. "There will be no way, short of conducting a war, to test fully a deployed BMD system, " wrote the subpanel. They concluded that:

> The problem of realistically testing an entire system, end-to-end, has no complete technical solution. The credibility of a deployed system must be established by credible testing of subsystems and partial functions and by continuous monitoring of its operations and health during peacetime.[50]

In addition to reliability, a battle management system must obviously resist attempts at penetration or subversion. This requirement mandates that extreme attention be given to overall system security. However, the subpanel realized that:

> There is no technical way to design absolute safety, security, or survivability into the functions of weapons release and ordnance safety. Standards of adequacy must, in the end, be established by fiat, based upon an informed consensus and judgment of risks.[51]

OTA concurs with these conclusions of the Fletcher subpanel.

[49] Ibid., p. 6-7.

[50] Ibid., conclusion 6, P. 7.

[51] Ibid., conclusion 7, p. 8.

NON-BMD APPLICATIONS

The same characteristics of BMD technologies which enable them to intercept and destroy ballistic missile attacks will also provide the capability to accomplish other military missions, including offensive ones. If not designed into the defensive system from the beginning, these other military missions may not be effectively performed; however, the technologies used to construct BMD systems might nevertheless also find use in different systems better suited to these other missions.

To understand fully the possible implications of deploying a BMD system, it is important to recognize the additional, non-BMD, contributions that BMD technologies could make to our strategy. Perhaps more importantly, we must understand what capabilities we might, de jure or de facto, have to concede to the Soviet Union, were we to decide that a mutually defended world was preferable to a mutually vulnerable one.

What Is "Offense?"

No military system easily lends itself to being characterized as strictly "offensive" or "defensive." A system's capabilities, such as overwhelming destructive power in the case of a nuclear weapon, can provide some clues. But in the final analysis, it is a weapon's use which becomes offensive or defensive, and even that is not unambiguous. A nuclear weapon used in an unprovoked attack on another country is an offensive instrument; one used to deter such an attack plays a defensive role. When a retaliatory weapon is actually used, the distinction becomes very difficult to make.

Ballistic missile defense technologies, which would not only be incapable of causing mass destruction but which would be able to prevent it, could be characterized as being primarily defensive. But there are also offensive roles in which they could be used—some inherent in any defensive system and others for which technologies developed for BMD might be well suited for, even if a BMD system itself did not seek to fulfill them. Some offensive roles, such as use to support a first-strike attack by blunting what would be a ragged retaliation, have been mentioned earlier in this report (cf. chapter 6) and will not be discussed further. Other aspects, however, will be presented in the following discussion.

Inherent Capabilities

Ballistic missile defense systems involve the precise application of power at long range. Depending on the characteristics of the sensors and weapons systems, the targets of that power might be many things other than ballistic missiles.

ASAT

Any BMD system will need to protect its space-based components against potential A SAT attack and will almost certainly require ASAT capability to defend itself. Since the same technologies applicable to boost-phase and midcourse defense can be adapted for ASAT, and since ASAT attack is a potent BMD countermeasure, the BMD mission and the ASAT mission are closely coupled. The connection is discussed elsewhere in this report (e.g., "Suppression," p. 175 ff.) and in the companion volume to this report, *Anti-Satellite Weapons, Countermeasures, and Arms Control.*

Anti-Aircraft

Those BMD weapons able to penetrate the atmosphere would be able to attack targets in the atmosphere if those targets could be located. Neutral particle beams and X-ray lasers, which cannot penetrate the atmosphere to low altitudes, could not be used in this role. Neither could kinetic-kill vehicles unless they could be made to function through reentry. Visible lasers, however, could attack aircraft targets in the absence of clouds.

Perhaps the more difficult part of the anti-aircraft mission will be finding the targets. Detecting an aircraft against a warm and cluttered Earth background is harder than spotting a satellite against the cold and relatively empty background of space. Cruise missiles, being smaller, will be even harder to find; application of "stealth" technology complicates the task still further.

Nevertheless, technology that is potentially capable of detecting aircraft from space is now under investigation. One of the objectives of the Teal Ruby sensor, a focal-plane mosaic array containing on the order of 100,000 infrared detectors which is scheduled to be deployed by the Space Shuttle, is to "provide proof of concept of stepstare mosaic for aircraft detection and tracking"[52] from space. Devices based on that technology could be powerful surveillance tools, and in conjunction with atmosphere-penetrating weapons could be effective against airplanes.

Attacking airplanes which are over the territory of another country is at present very difficult. If that task were made easier, it could

"Rockwell International Satellite Systems Division diagram.

Photo credit: U.S. Air Force

TEAL RUBY will develop technology for a space-based surveillance system capable of detecting and tracking aircraft near the Earth's surface.

have profound strategic implications. Crucial U.S. command and control functions are now conducted aboard airborne command posts, which are mobile and difficult to find. These planes supplement ground facilities, which at present are vulnerable to nuclear attack. Should these aircraft also become vulnerable to Soviet attack, the command and control structure of our nuclear forces would be seriously weakened and would have to be redesigned.

A BMD system does not have to be able to attack aircraft. However, should one be developed, the advantages of also providing it with anti-aircraft capability may be compelling.

Precision Ground Attack

Weapons which penetrate into the atmosphere can also attack targets on the ground. There are at present lots of other ways to destroy terrestrial targets, so ground attack missions might not be an attractive option for a ballistic missile defense. Furthermore, ground targets would probably be easier to protect than ICBM or satellites from the types of damage that a ballistic missile defense-capable system could inflict. It may therefore be the case that space-based weapons systems would be grossly inefficient for attacking targets on Earth. However, such a system might provide the ability to do so with essentially no warning, which no existing weapon can do; moreover, even if the system is deployed for other reasons, some amount of ground-attack potential might nevertheless be present. Although the optimal weapons for space-to-earth attack may not be the best for ballistic missile defense, they would probably be difficult to ban under an arms control regime which allowed space-based BMD weapons.

CONCLUSION

There is a wide variety of technologies which could, in principle be assembled to form a space-based BMD system. Candidate technologies for kill mechanisms include various types of lasers, kinetic-energy weapons, and particle beams. No physical law would prevent the construction of a workable system, consisting of boost phase, post-boost phase, midcourse, and reentry phase layers. Each technology, however, is limited by physical laws. These limitations complicate, but do not eliminate, the possibility of a working system based on that technology. Such problems relate, for example, to: the limitation on the distance traveled in the time available, due to finite velocities (kinetic-energy weapons); inability of the energy-delivery device to penetrate the atmosphere effectively (particle beams, X-rays, possibly kinetic energy); the curvature of the Earth (pop-up systems).

For all of the methods envisioned, much research is necessary to determine scientific, engineering, and economic feasibility. All methods except the X-ray laser and very bright optical or ultraviolet lasers with very low slew times require a large number of space-based satellites with high performance reliability and with access for maintenance. To the extent that sensor satellite requirements exceed those for space-based weapons platforms, all systems will require large numbers of satellites. In general, the higher the attainable power, and the faster the retargeting time (for directed-energy weapons), the fewer battle stations are needed. Great improvements in computer speed, reliability, and durability are needed to achieve a workable system. Current research in computer hardware development gives cause for some optimism in that area. However, even greater advances are required in software capabilities.

A new space shuttle with about three times the capacity of the present one may have to be developed for most options. An alternative would be to reduce greatly the cost of placing material in orbit using the shuttle or something with roughly the same payload capability. If Soviet attack during the deployment phase is considered likely, this shuttle should be able to defend itself during and after insertion into orbit, or it must be defended by satellites already deployed.

The defensive systems discussed are yet to be proven, and are very far from being developed and deployed. In a number of essential particulars, improvements in performance of several orders of magnitude (factors of 10) will be needed.

Operational issues, rather than technical ones, may come to determine questions of technical feasibility. These operational issues are of two sorts—the ability of a defensive system to anticipate and cope with offensive countermeasures, and the confidence which defensive planners can have in a strategic defense which cannot be tested under fully realistic conditions.

An issue to be resolved is the susceptibility of sensors to defeat by various countermeasures. Their sensitive nature, required for long-distance detection, also renders them vulnerable to various levels of blinding. Another general counter-tactic is the emplacement of space mines, which can be used against sensor satellites or battle stations. For each technology there are many possible countermeasures, both active and passive, which can be taken by the offensive forces. Some are simple and straightforward, even with today's technology. Others are more complicated and would require great effort, perhaps comparable in magnitude with the technology they would counter.

Defensive systems, if deployed 10 to 20 years from now, will have to deal not only with today's countermeasures, but also with those which will exist 10 to 20 years hence. For these countermeasures, there may well be counter-countermeasures which are feasible. The eventual outcome of the contest between measures, countermeasures, and counter-countermeasures cannot be predicted now.