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EXOATMOSPHERIC BALLISTIC MISSILE DEFENSE: A TECHNICAL OVERVIEW

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Preface

When this analysis was begun in 1981, a two-tier ballistic missile defense system based on conventional rockets was a likely option for reducing the perceived vulnerability of United States land-based ballistic missiles. The basing mode of MX missiles was being hotly debated, and for a time it seemed possible that the MX might not be deployed at all.

Since then, much of the strategic debate appears to have been resolved. Having found no better basing mode, the Administration (with the support of Congress) is preparing to place the MX missiles in the Minuteman silos which were once considered so vulnerable. After President Reagan's "Star Wars" speech of March 1983, the nation seems ready to develop exotic new defense systems intended to destroy Soviet ICBMs as they are launched. Such grand ideas make conventional defense systems intended to destroy warheads late in their flight appear somewhat dated by comparison. The timeliness of an analysis of exoatmospheric ballistic missile defense systems (such as the one described here) might understandably be questioned.

Nevertheless, many of the issues which arise in examining an exo defense system also arise essentially unchanged in any discussion of exotic systems. The defense still requires an early warning system to detect an attack in its early stages. Targets must be identified and correctly assessed in spite of penetration aids deployed to foil discrimination between real warheads and decoys. The complete system must be reliable enough under stress to achieve realistic strategic objectives. Not only do many of the issues remain unchanged, but the technologies applicable to their solution are often comparable. For example, detection and discrimination through infrared imaging, essential for exoatmospheric defense, is also expected to play a role in any exotic defense system. Similarly, navigation, guidance, and tracking technology will be as indispensible for exotic systems as for more conventional systems. Despite appearances, previous analyses of strategic doctrine are not immediately made obsolete by the projection of a new doctrine.

Moreover, strategic concepts seem to be cyclic. Often they enjoy a vogue, then fall into oblivion, only to be resurrected much later. The cycle appears to span about twenty years. Perhaps this is the interval required for the cleverness of a "novel" concept to appeal to a new generation unfamiliar with the inherent fallacies which earlier brought the concept into disrepute. Many will remember that civil defense was ardently pursued in the early sixties, only to be forgotten until recently. Likewise, the quest for an anti-ballistic missile system began even as ballistic missiles were being developed. Designs relying on ground-based rocket interceptors were later supplemented with schemes for networks of satellites possibly armed with microwave or nuclear particle beam weapons. Such efforts were largely forgotten after the signing of the ABM Treaty in 1973. Many would argue that the Treaty between the two superpowers was made possible by the mutual realization that achieveable ABM systems offered little if any strategic advantage, especially in comparison with their cost. Now, twenty years after their first appearance, defense systems against ballistic missiles are attracting interest once again.

Therefore, if some of the analysis which follows appears to be dated, the analyst may retain some confidence that it may still become relevant for strategic debates of the future. Unfortunately, we cannot yet look forward

with confidence to the day when such discussions about strategic nuclear weapons systems become obsolete along with the weapons themselves.

This project was undertaken while I was a part-time Postdoctoral Research Associate at MIT's Center for International Studies. I wish to thank Professor Jack Ruina for the opportunity to join the Center in this position, any my colleagues at the Charles Stark Draper Laboratory for their indulgence during this partial leave of absence. I am grateful for many informal discussions with colleagues both at CIS and at Draper, and I am particularly indebted to Dr. Ashton Carter (who had prepared the Ballistic Missile Defense analysis for the MX Missile Basing report for the Office of Technology Assessment) and to Dr. Stephen Weiner of MIT's Lincoln Laboratory.

I. Introduction - The Strategic Context

For almost two decades, US strategic deterrence has rested primarily on the survivability of its strategic triad. Each of the three independent nuclear weapons systems which presently make up this triad - the land-based Minuteman and Titan ICBMs, the submarine-based Poseidon and Trident SLBMS, and the B-52 strategic bombers (now being armed with cruise missiles) - is designed and operated so that in some respect it is inherently safe from a pre-emptive attack. The ICBMs are sheltered in hardened silos, the submarines are hidden in the oceans, and an important fraction of the bomber force could escape given early warning of an attack. According to strategic orthodoxy, as long as each component of the triad is independently survivable, the United States can remain confident that no surprise attack could disable its capability for a devastating counterattack.

However, the invulnerability of one of the components of the triad, the ICBM force, is now being called into question. Until recently, it was generally accepted that Soviet missiles lacked the accuracy necessary to destroy US ICBMs in their hardened silos. Recent observations of Soviet missile tests have suggested to many commentators that new Soviet ICBMs equipped with powerful and accurate multiple warheads now make it possible in theory for the Soviets to destroy US ICBMs in a surprise attack. Although not all commentators agree that the Soviets now have this capability, the accuracy of US ICBMs is currently being upgraded and a similar Soviet capability cannot be postponed indefinitely. Whether the Soviets would ever choose to exercise this capability or whether such an attack would be successful if attempted, the very threat itself is unprecedented and has forced a fundamental reconsideration of US strategic policy. The concept of an invulnerable strategic triad, with the security it offers, will be abandoned only with the greatest reluctance.

Preserving the survivability of the ICBM force was the goal of the mobile Multiple Protective Shelter (MPS) deployment scheme proposed for the new MX missile by the Carter Administration and the Air Force. By multiplying the number of aim points which the Soviets would have to target, MPS might make it impractical for the USSR to attack the US ICBM force. This scheme was dropped by the Reagan Administration for technical and political reasons.

By rejecting the MPS basing scheme while insisting on the preservation of the ICBM force, the Reagan Administration has deepened an already awkward dilemma. Other more exotic ideas for preserving ICBMs have been suggested, including launching the missiles while under attack (which might increase the risk of an accidental nuclear war), carrying the missiles in small submarines or aircraft, or burying the missiles in very deep underground shafts. Closely-Spaced Basing, also called Dense Pack, has been proposed by the Administration and rejected by Congress. In this scheme, the missile silos would be so close together that the detonation of one warhead over one silo would destroy or disable most of the remaining warheads, thus protecting the other silos. More recently, a Presidential advisory committee has urged the development of a small mobile missile. Even if it was concluded that such a missile is a practical solution to the problem of ICBM vulnerability, the new missiles could not be ready for deployment much before 1995. All of these ideas have serious technical, economic, or political drawbacks. Consequently, it is becoming likely that the Administration will soon feel itself driven to deploy a Ballistic Missile Defense (BMD) system in support of whatever basing scheme is adopted for MX.

Of course, the hope for a defense against ballistic missiles has been given a new impetus by President Reagan's speech of March 1983, in which he called for new technology to defend all of the US from a Soviet ballistic missile attack. A defense based on beam weapons lies far in the future and is beyond the scope of this report. Still, an exoatmospheric defense system based on interceptor rockets and able in principle to defend large areas might be seen by some as a near-term alternative to beam weapons. Such a system could be extrapolated from the ballistic missile defense system to be described here.

Since the signing of the ABM Treaty between the US and the USSR (as part of the SALT I process), most people have considered BMD (as it is now known) a dead issue. The Treaty,[1] with its 1974 Protocol and additional understandings, limits ABM deployment to an essentially negligible force on each side and significantly restricts the development of ABM systems of all types. In principle, the Treaty remains in force indefinitely, but it may be reviewed and amended at any time by common consent of the US and the USSR. Periodic reviews are required at five-year intervals; the most recent was during 1982. Further, the Treaty may be abrogated unilaterally on six months' notice, a negligible period in terms of the development and deployment of an ABM system. The ABM Treaty remains in force because whatever strategic advantages may be perceived for ABM deployment are outweighed by political costs as well as the implicit threat that the USSR could build its own defense if the Treaty were abandoned.

Proponents of BMD are often heard to argue against the Treaty that it enshrines the concept of Mutually Assured Destruction (MAD) as the guarantor of peace in a nuclear world. In the definition of MAD which these proponents ascribe to ABM opponents, peace is preserved because each side is held as an undefended hostage to the other's nuclear weapons. Given this definition, it would be undesirable to deploy an ABM system because that action would upset the stable impasse of offensive weapons. Because the proponents find this concept of MAD unconscionable, they reject any policy they see arising from it.

In fact, opponents of ABM argued[2] that MAD was not a strategic doctrine but an interpretation of the prevailing strategic situation. That the US and the USSR were hostages to each other's strategic forces was not desirable, it was unavoidable. Secretary of Defense Robert McNamara had said in 1967[3] that if effective means were available to defend US society from Soviet nuclear forces, it should be deployed. Unfortunately, such means were not then available, although not for lack of trying. Defending US cities had been the goal of US ABM technology throughout the 1960s. This technology was embodied in three ABM systems, Nike-Zeus, Nike-X, and Sentinel. Each of these was proposed for deployment and rejected on the evidence that it could not accomplish its assigned mission.

Historically, ABM systems were first developed in the hope of defending all of the US from a nuclear attack. In an attempt to accomplish this goal, long-range interceptor missiles such as Nike-Zeus and later Spartan were developed. These carried large nuclear warheads to destroy attacking warheads at high altitudes before they re-entered the atmosphere. In addition, the Sprint missile which carried a smaller nuclear warhead was developed to allow interceptions after the warheads re-entered but before they reached their targets. Such systems required powerful radars which could reach the necessary ranges for detection and tracking, in spite of disruptions such as nuclear fireballs and distractions such as decoys and chaff. Still, the goal of defending soft targets such as cities from a sophisticated ICBM attack has been elusive. A soft target can be devastated by a large nuclear weapon even if it is detonated at a range of up to ten miles. Major cities are such priceless strategic targets that to be effective the defense must be virtually impenetrable. It is now generally accepted even by BMD proponents[4] that an effective ABM defense of cities is not possible in the near future, and this conclusion is the principal technical basis for the ABM Treaty.

The development of ABM for area defense climaxed in 1967, late in the Johnson Administration, with the announcement of the Sentinel ABM system. Because a general defense against a sophisticated Soviet attack was officially acknowledged to be unfeasible, Sentinel was directed against the improbable threat of an unsophisticated Chinese ICBM attack. When the Nixon Administration took office in 1969, the Sentinel program was modified and renamed Safeguard. The Safeguard program was intended to defend US ICBMs against a light Soviet attack. However, Safeguard was no more credible in this new role than Sentinel had been in its earlier role. All of the available components for Safeguard, such as radars and missiles, had been developed for area defense and were not optimal for ICBM defense. Safeguard deployment was overtaken by the ABM Treaty, and the only Safeguard site to be completed was closed in 1976.

Nevertheless, research and development for BMD has continued within the constraints imposed by the Treaty. By remaining current in BMD technology, the US hopes to discourage the USSR from renouncing the Treaty and deploying its own systems. The US also remains ready to deploy BMD if the technology warrants it and if the strategic situation requires it.

The main goal of this continuing program has been the defense of hard targets, such as Minuteman ICBM silos. Compared with city defense, hard target defense is much less demanding. An incoming re-entry vehicle (RV) can be allowed to come within about a mile of a defended hard target before it is intercepted. This makes it possible to deploy a defense system for which the range of the interceptor is reduced and a less powerful and expensive radar is required. Also, the discrimination between true RVs and decoys becomes very much easier at low altitudes due to the sorting effect of atmospheric drag. Finally, since only a fraction of the ICBM force must be preserved to ensure deterrence, the defense system can tolerate moderate "leakage".

The Site Defense Program which followed the signing of the ABM Treaty led to a system designed to defend a cluster of hard targets such as Minuteman silos. It called for an interceptor with a range of several miles, shorter than that for Sprint but still long enough to defend several Minuteman silos simultaneously. The data from several radars could be combined or "netted" to circumvent the disruption of nuclear fireballs. Faster commercial computers which could cope with the huge volume of data to be handled in real time were integrated into the system.

The Low Altitude Defense System (LoADS)[5] was specifically designed for the defense of MX missiles in an MPS basing mode, but MPS was cancelled before the LoADS system was actually developed. The design called for a small, short-range interceptor with a nuclear warhead of several kilotons, and a correspondingly small phased-array radar. A LoADS defense unit (with several interceptors to defend both itself and the MX missile) would be placed in a shelter next to the shelter occupied by the missile. In order to stay close to the missile without disclosing its location, the LoADS unit itself would have to be mobile and deceptively based. Deceptive mobile basing of the defense therefore served two distinct but coincident functions for this deployment. First, the offense could not attempt to destroy the defense unit before attacking the MX missile because the location of the defense unit would be hidden. Second, the defense unit would not give away the location of the missile it defended.

Under the new name Sentry, the LoADS design remains the most likely candidate for an endoatmospheric hard target defense system.

The short range of a terminal defense system has the disadvantage that each individual hard target or cluster of hard targets requires a separate complete defense system (unless the defense is mobile and deceptively based). Alternatively, one long-range "area" defense system could defend many targets (hard or soft) simultaneously. The defense then has the option of using all of its resources to defend only a fraction of its defended targets. For example, the defense could choose to defend a subset of the ICBM force large enough to ensure retaliation after an attack, allowing the remaining ICBMs to be destroyed. Since the attacker would not know in advance which targets would be defended, he would have to structure his attack on the assumption that all of the targets would be defended fully. This "preferential defense" is a form of "leverage" because it requires the attacker to allocate large offensive resources to overcome smaller defensive resources.

In spite of its potential advantages, area defense of hard targets has been impeded by many of the difficulties which forestall population defense. The example of the Spartan missile illustrates this. Originally designed as a long-range interceptor for the Sentinel area defense system, it was later incorporated into the Safeguard ICBM defense system. To operate at long range, Spartan required a powerful ground-based radar which was both costly and vulnerable. It could be disabled by direct attack or by blackout from nuclear fireballs in the atmosphere. The large nuclear warhead carried by the Spartan missile might itself contribute to blackout. The radar apparently had little capability for discriminating RVs from decoys before they re-entered the atmosphere. Presumably, this was not considered necessary, either because few decoys were expected or because a large well-placed warhead could destroy several RVs simultaneously. These considerations made Spartan an unconvincing defense system. The subsequent development of multiple re-entry vehicles (MIRVs) and sophisticated penetration aids (penaids) has since made exoatmospheric defense even more difficult.

BMD proponents now suggest that novel optical technology and non-nuclear kill (NNK) can overcome these problems. Ground-based radars could be replaced by optical sensors lofted above the atmosphere. Incoming RVs could be destroyed individually by many small rockets called kill vehicles (KVs) carried by one interceptor in place of a nuclear warhead. Since the exoatmospheric engagement takes place above the atmosphere before the RVs re-enter, several minutes are available to detect, track, intercept, and destroy the RVs, rather than the several seconds available for engagements in endoatmospheric defense.

Further, this exoatmospheric area defense system might be supported by an endoatmospheric terminal defense system such as LoADs to form a layered system. The attraction of the layered system in simple terms is that the leakage rates for the two systems might be multiplicative. For example, if each of the two component systems had a 20% leakage rate, the combined systems might have an overall leakage rate of 4%, according to proponents.[6] In special cases, the two component systems might be synergistic, mutually supporting each other so that each is more efficient in combination than alone.

Congress has directed the Administration to produce a permanent plan for basing the MX missile; a basing plan which includes BMD has been among the options considered. Defending the existing Minutemen ICBMs is another possibility, but apparently it has not been considered. It is generally accepted[7] that present terminal defense technology is adequate to allow deployment of a system such as LoADs with relatively low technical risk. On the other hand, the development of exoatmospheric defense has received much less emphasis, that is, only about 5-7% of the total BMD budget in recent years (about $350-450 million since 1966).[8] The new exoatmospheric technology has not been fully tested and will continue to represent a much greater technical risk during the next few years. If the Administration chooses to deploy BMD, it may choose to deploy a terminal system alone, deferring any decision on the exoatmospheric "overlay", or it may choose to develop and deploy both the terminal system and the overlay simultaneously, accepting the risk associated with the overlay development.

In either case, the utility of the endoatmospheric system may ultimately depend critically on the performance of the overlay, whenever it is deployed. Consequently, a decision to deploy an endo system alone at least partially presupposes the eventual successful development of an exoatmospheric system.

The potential availability of two very different types of BMD presents several options for BMD deployment, namely:

1) endo only;

2) endo-exo (endo dominates);

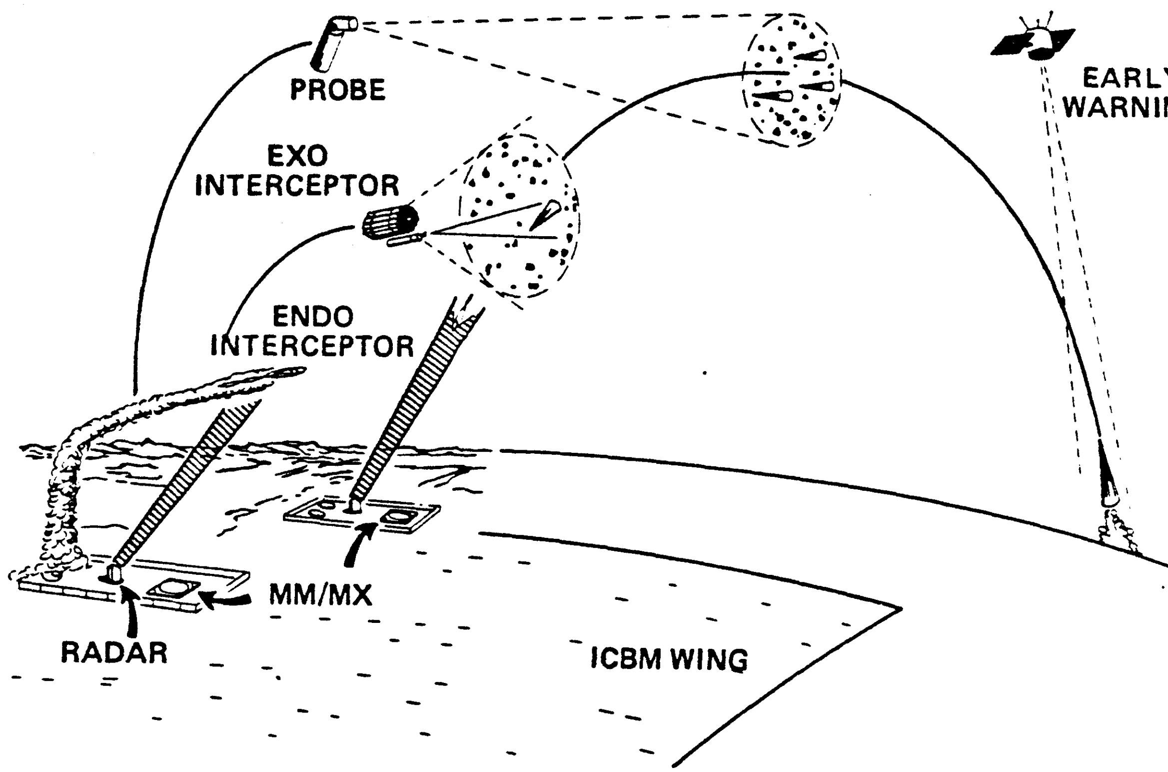
3) endo-exo (exo dominates);

4) exo only.

The success of an endo only defense may depend critically on the basing scheme for the ICBMs it defends. For example, an endoatmospheric defense system such as LoADS was attractive while MPS was a viable basing option for MX because it very effectively utilized the concept of leverage. Because each of the 200 MX missiles would be hidden in any one of 23 shelters, the Soviets would have to aim at least one RV at each of these shelters to ensure destroying the missile. Thus MPS would force a ratio of at least 23 RVs per MX destroyed, for a total of 4600 RVs. If a LoADS unit were also hidden among the shelters, its interceptors could shoot down the RVs aimed at the shelters containing the MX and the LoADS unit while ignoring the remaining RVs. Then the Soviets would be obliged to aim at least two RVs at every shelter, one to draw the defense and the second to destroy the missile. The presence of LoADS effectively doubles the already large number of RVs necessary to destroy the MX missiles. The performance of LoADS need not be very high to enforce this advantage. It is strategically effective if the system can destroy merely 50% or more of the RVs it is assigned to intercept. The key feature of this scheme is that MPS basing and deceptively based defense operate synergistically to gain leverage that neither enjoys alone. MPS basing reduces the number of RVs attacking each target to a level where a relatively simple defense system can gain additional leverage.

In the absence of MPS basing for MX, the Soviets will be able to target their RVs much more densely. For example, it is conceivable that by 1990 the Soviets might be willing to aim as many as eight warheads at each of 1000 Minuteman missile silos, should they chose to expand their arsenal as the US expands its own. (One reason given for dropping MPS was that the Soviets might be willing to aim as many as 9200 RVs against it.) In this situation,

Figure 1 - US Army Scenario for Exoatmospheric Ballistic Missile Defense
(Public Affairs Office, Ballistic Missile Defense Organization)



LAYERED DEFENSE SYSTEM

A Layered Defense concept combines many of the BMD program's major thrusts. The artist's conception above depicts a typical two-tier BMD scenario. After early warning is received, probes carrying optical sensors would be the first element of a Layered Defense to acquire attacking ICBMs. Next, the "overlay's" optically guided "exo" interceptors thin the attack with their nonnuclear warheads, destroying many of the attackers above the atmosphere. The remainder of the attack is engaged by the "endo" low altitude interceptors of the terminal defense "underlay."

the endo system must be capable of destroying all eight RVs in order to protect the silo. Unless the endo system is deceptively based or given a long range to cover more than one missile silo simultaneously (an option which provides leverage but places difficult and expensive requirements on the system radar and interceptors), eight interceptors must be provided for each of the 1000 silos. To be sure of destroying all eight RVs with adequate confidence, the reliability of destroying any one RV must be quite high. Further, the offense may attempt to overcome the defense by adjusting tactics. For instance, the offense may detonate several warheads in quick succession above the defensive radar sites (in a so-called "ladder attack"), thus momentarily blinding the radars while later RVs sneak through to destroy the defended missile silos.

To discourage such tactics, the US might be willing to deploy a light exoatmospheric defense system above the endo system. This overlay would attempt to break up the coordination of a dense attack, operating synergistically in support of the endo system. The endo system would still be almost as elaborate as before in order to defend against all the remaining RVs. The overlay in this case is added to the endo defense essentially to allow the endo defense to operate as intended.

Alternatively, the exo system might be designed to destroy most of the incoming RVs, leaving only a few leakers to be swept up by a much lighter endo system below. The exo system with its much greater range can defend many silos simultaneously from one defense site, thus offering considerable leverage through preferential defense. Nevertheless, if the exo system is to carry the major burden of defense, it must achieve a high level of performance in order to assure the preservation of the ICBM force in the face of a dense Soviet attack.

Because the endo system is technically more advanced and because the performance requirements on an exo system would be very high in the absence of any supporting endo system, the option of deploying an exo system alone does not appear to be given serious consideration.

The evaluation of BMD performance for each of these deployments depends critically on the composition of a postulated Soviet attack. If the Soviets were willing to attack the ICBM force at all, one must presume that they would be willing to pay the price necessary to destroy it. Deploying a BMD system might indeed raise this price by a calculable amount, obliging the Soviets to divert warheads from other targets or to build more warheads, but it may not dissuade them from attacking unless the BMD system were convincingly unassailable.

While the Reagan Administration remains committed to the deployment of the MX missile, ICBM vulnerability remains a key issue to be resolved, and the outcome of the debate is unpredictable. In view of these immminent strategic decisions, it is timely to examine the technical basis for exoatmospheric ballistic missile defense.

II. A Scenario for Exoatmospheric Ballistic Missile Defense

The entire flight of an ICBM lasts only about 30 minutes. The boost phase requires about 2 minutes, lifting the missile payload out of the atmosphere and giving it most of the velocity required to reach its targets. Shortly after the booster rocket falls behind, the MIRV "bus", under control of the guidance system, sequentially adds increments of velocity and deploys each of its re-entry vehicles (RVs). In the course of this RV deployment, the bus may also deploy a variety of penetration aids for confusing the defense. The booster itself may be exploded into fragments to add to the confusion.

All these objects travel in ballistic trajectories for approximately 20 minutes before they re-enter the atmosphere. At re-entry, almost all the light material accompanying the RVs (booster fragments and penetration aids) are quickly retarded and destroyed by the friction of the atmosphere. The heavy RVs plunge through the atmosphere to their targets in less than a minute.

A possible exo defense scenario is described in official Army BMD public relations literature.[9] One should recognize that this is not the only possible scenario; alternative scenarios can readily be imagined. Exo defense technology is still so far from maturity that the final form of an exo defense remains largely speculative. Nevertheless, this official scenario illuminates the basic features of exo defense and forms the basis for the analysis which follows.

About ten minutes before the arrival of the first RVs, the US exoatmospheric defense system would launch several "probes" into ballistic trajectories above the atmosphere. Since the launch and positioning of the probes would itself require about three minutes, the probes would have about five minutes to assess the attack in detail and call for appropriate defense measures. The trajectories of the probes would allow them to remain above the atmosphere for several minutes in order to view and assess an extended attack. The probes would carry infrared telescopes with sensors in three optical bands to gather data on the trajectories and emissions of each of the objects making up the attack. The computed trajectories would indicate the targets under attack and allow calculation of intercept trajectories. The infrared emissions would indicate the surface temperature of each object, providing clues for separating the RVs from all the penetration aids. The massive RVs would tend to maintain their temperature and therefore their infrared emission would tend to remain constant; all the lighter objects would tend to cool more rapidly to the equilibrium temperature of space.

As the RVs approach re-entry, interceptor rockets would be launched to meet them. Each interceptor would carry ten or more "kill vehicles" (KVs), small rockets with separate guidance systems which would be deployed after the interceptor leaves the atmosphere. Each KV would be assigned an RV within its range. The KV would home on its assigned RV and destroy it either by direct collision or with conventional explosives.

Because the probe's sensors would generate huge amounts of data, the probe would carry a sophisticated computer to process the raw data before transmitting it back to the ground. In fact, plans call for special mobile cryogenic computers capable of 40 million instructions per second (MIPS); for comparison, the Cray 1 or Cyber 205 "super computers" which are now available for earth-based applications are capable of about 100 MIPS .

The entire defense would be co-ordinated by a large ground-based commercial computer called the Battle Manager which would be equipped with the interfaces necessary to communicate with the early warning systems, the probes, and the interceptors, and with the human operators who ultimately supervise the system.

A key feature of this system which distinguishes it from all earlier ABM systems is the reliance on non-nuclear kill (NNK). As noted earlier, the Spartan exoatmospheric system destroyed RVs by exploding a large thermonuclear warhead. The resulting flux of thermal x-rays could be expected to damage RVs even at a distance of about 10 kilometers, so the guidance accuracy required for Spartan was not great. The new system avoids the use of nuclear warheads, but in order to destroy the incoming RVs the system must be able to place the KVs within a few feet of their targets.

Still, achieving this goal offers great rewards.[10] The system avoids the political problems encountered in producing and deploying large numbers of additional nuclear weapons. It does not draw on short supplies of critical nuclear materials. The interceptors could be launched without the need for Nuclear Release Authority (NRA) in the tense moments at the start of a nuclear attack. The system would not need to protect itself from the effects of its own nuclear explosions (self-induced effects). Finally, the system could be tested without violating the Nuclear Test Ban Treaty (although the ABM Treaty may be another matter).

III. Generic Features of an Exo Defense System

On the basis of the foregoing scenario, one can identify the following functions which are implicit in exoatmospheric defense:

1) Preferential defense (in specific circumstances);
2) Early warning;
3) Passive infrared tracking;
4) Discrimination;
5) Tracking and discrimination combined: The forward acqusition system;
6) Multiple kill vehicles;
7) Computation and battle management;
8) Communications.

It must be remembered that the success of exo defense depends on the successful operation and coordination of every one of these concepts.

While each function is vital to exoatmospheric defense as it is currently being described, some of the functions are more easily accommodated in system design than others. These key functions are described below, each with a brief assessment of its significance for exoatmospheric system development.

1) Preferential defense. A system defending ICBMs must preserve only a fraction of the ICBM silos in order to ensure a retaliatory capability. The defense maximizes its efficiency by concentrating all its resources on defending a fraction of the silos, allowing the remainder to be destroyed. Since the offense does not know in advance which silos are being defended, a

large increase in offensive resources is required to offset a small increase in defensive resources.

Preferential defense presupposes that the defense can afford to sacrifice a major fraction of its ICBM silos. In addition to losing all the undefended silos, the defense must also expect to lose some of the defended silos as a consequence of unavoidable leakage. (Tolerance of controlled leakage is one of the features which distinguishes point defense of silos from area defense of cities.) The defense must therefore manage its preferential defense strategy in such a manner that after sacrificing some silos outright and losing others to leakage, it still retains enough ICBMs for a credible counterattack.

As a simple example, assume the US wishes to guarantee the survival of 400 EMT (equivalent megatons) in its ICBM force after a Soviet attack. (For warheads with yields of less than a megaton, the equivalent megatonnage of the warhead is the square root of the actual megatonnage.) The surviving 400 EMT could be represented by 75 MX missiles, each with 10 warheads of 0.3 MT each. If the US possessed 200 MX missiles, and expected 25 to be lost to leakage during an attack, then preferential defense could be exercised to sacrifice 100 MX missiles while defending 100, so that about 75 missiles would remain. The Soviets would be obliged to assume that all of the 200 missiles were fully defended. On the other hand, if the US possessed only 100 MX missiles (and nothing else . . .), it could not afford to sacrifice any of the missiles outright, and no advantage could be gained from preferential defense.

Preferential defense therefore depends on the availability of targets which can be sacrificed. If 1000 Minuteman missiles were protected by an exo BMD system, perhaps half of these could be sacrificed while still preserving a credible deterrent. On the other hand, if 100 MX missiles were protected, probably all must be defended, and preferential defense is nullified. Additional MX missiles might be deployed in anticipation of their eventual sacrifice, but the cost would probably be prohibitive. In other words, preferential defense would not be cost-effective where additional ICBMs must be deployed to make it viable. Alternatively, the ICBMs might be deployed in an MPS basing mode in which the empty shelters could be sacrificed. Even so, the additional shelters might be so costly that the cost of preferential defense would become prohibitive.

Further, the operation of preferential defense is not straightforward, because the offense may adopt tactics to nullify it. In particular, the offense may choose to spread its attack over time so that the defense cannot assess the full attack before it is obliged to commit its interceptors. Then the defense cannot assume that the offense's RVs are evenly distributed over all the targets, and must resort to a technique called adaptive preferential defense which considerably dilutes the advantage of preferential defense. On the other hand, while extending its attack, the offense must hope that the defended missiles cannot be launched in retaliation before the extended attack is complete. The MX missile is in fact being designed to fly out through the debris of a nuclear attack, insofar as that is possible.

2) Early warning. The system launches its interceptors from ground level and makes its intercepts above the atmosphere. Hence several minutes' warning must be provided from an external warning system.

The tremendous heat generated by the ICBM boosters would be detected immediately by the infrared (IR) sensors aboard geostationary satellites of the type expected to be deployed by the US in the late 1980s. These satellites would quickly alert US forces of the impending attack. Further, they could provide general information about the size of the attack (for example, the number of ICBMs launched), although they would not be able to discern the intended targets of the missiles. Since some of these satellites would be in high geostationary orbits, the USSR could not easily disable them without alerting the US to the danger of an attack. Nevertheless, should the satellite network fail, the US might still depend on warning from the ground-based radars of the Ballistic Missile Early Warning Systems (BMEWS).

The requirement for early warning to ensure the survivability of the ICBM force establishes a common failure mode for both the ICBM force and the bomber force. Already the bomber force requires early warning to allow the bombers to escape under attack from their vulnerable fixed bases. If the ICBM force becomes dependent on an exo BMD system for its survivability, and if in turn the exo system depends on early warning to initiate its defense, then a failure of the early warning system simultaneously places both forces in jeopardy. The deployment of BMD therefore makes the survivability of the early warning system even more critical.

The early warning satellites could detect the launch of Soviet ICBMs and therefore provide about 30 minutes' warning of an attack. In their high orbits, the satellites would be relatively immune from surprise attack. Several kinds of attack can be imagined. A direct-ascent rocket attack could be observed and reported as it is launched and at least 1/2 hour (probably much longer) before it could reach a satellite in high orbit. A ground-based laser attack would be instantaneous, but the distance between laser and satellite would make it difficult to concentrate the laser beam on its target. Also, the satellite could be hardened to withstand such attacks. Yet another possibility is that the Soviets might station anti-satellite satellites close to strategically important US satellites, in order to be able to destroy them quickly in a surprise attack.

Ground-based radars (BMEWS) can also provide early warning of a Soviet attack, but only after Soviet RVs rise high in their trajectories, perhaps 15 minutes after launch. This would leave a much smaller interval of about 15 minutes in which to carry out the defense, and the exo system must be carefully constructed to ensure its ability to respond on such short notice. The radars themselves are vulnerable to surprise attack either by SLBMs or by low-flying aircraft.

While it is hard to imagine a surprise attack capable of neutralizing both satellites and radars without giving any warning, early warning might be systematically suppressed in a protracted nuclear war (such as envisioned by the present Administration). With difficulty, one can imagine improbable scenarios in which the Soviets carefully destroy critical components of the early warning network without provoking a response from US ICBMs. Then the ICBM force would remain in its shelters, unprotected by the exo system which would be paralyzed without early warning.

Even in peacetime, the early warning system is the most exposed and vulnerable part of the defense system. Both the US and the USSR indulge in a habit known as "tweaking", in which the surveillance sytems of the opposing side are carefully teased to elicit a response. The responses to tweaking provide valuable intelligence on the capabilities of these systems, which in turn can be used to devise strategies for overcoming them in time of war.

3) Passive infrared tracking. The incoming warheads must be tracked to compute target points and interception trajectories. In place of ground-based radars which are vulnerable to direct attack and nuclear blackout, the exo system uses a rocket-borne optical system. Lofted radars are thought to be too cumbersome for this mission and would have poor angular resolution. Since the RVs may be eclipsed by the earth's shadow, the intrinsic thermal emission of the RVs, which peaks in the infrared, is the only reliable emission for tracking. Only the angular position of the RV with respect to the sensor can be measured directly by such a passive system. A range measurement would require an active component such as a pulsed laser, but the distances to be measured are too great for successful ranging.

Tracking serves several purposes in exo defense. At a minimum, tracking accuracy must be sufficient to allow the computation of trajectories for the interceptors and to permit the individual KVs to acquire their targets. Also, if the exo system is exercising preferential defense (in which not all of the ICBM silos are defended), then the intended target of each individual RV must be determined in order to decide whether that RV should be intercepted or ignored.

The precision of angular measurements is limited ultimately by optical diffraction in the inevitable presence of noise. Although the system relies on long infrared wavelengths (5-20 micrometers) and the aperture of the observing optics is limited (less than 0.5 meters), it is possible to contemplate resolution approaching 20 microradians. This angular resolution corresponds to a length of 20 meters at a range of 1000 kilometers.

A distinction should be made between resolution and accuracy. Even if an object is not resolved, its angular position can be measured to a precision within a small fraction of its image diameter or within a fraction of a digital picture element. Careful engineering analysis is necessary to match the optical imaging properties of the system to its digital sampling properties. Accuracy also implies that the object can be located in an absolute frame of reference. Optical distortions must be compensated, and the optical system itself must be carefully stabilized. (Stabilization can be aided by observing the positions of known astronomical objects within the probe's field of view.)

In order to derive a complete track in three dimensions, the range from the probe to each object must be inferred somehow from the angular measurements. Two methods have been suggested for ranging.

The first method relies on the angular rate at which the object deviates from a straight-line trajectory under the known influence of gravity. Only one probe is required for gravitational ranging, but the uncertainty achievable appears to be greater than several hundred meters in range during flight.

(The accuracy of this technique is known to be compromised when both the probe and the observed object are subject to the same acceleration due to gravity. It has been suggested that the probe should be equipped with a small sustainer rocket to provide an acceleration difference and also to maintain the probe aloft for a longer period.)

The second method requires at least two separate probes to determine the range by triangulation (parallax). Since the probes must sight along almost parallel paths, the accuracy of the inferred range will not be as great as the accuracy of the two cross-range co-ordinates. Nevertheless, range accuracies of about 50 meters can be envisioned. The increased accuracy of triangulation over gravitational ranging appears to make it the method of choice.

The velocity of each object may also be inferred from several successive measurements of object position in three dimensions.

If two or more probes are launched, an additional task will be to catalog all the approaching objects so that the images of each object from the separate probes are correctly associated with one another. Since at first only angular positions are known, the position of an object in three dimensions is not certain; each object can be localized only along a radial centered on a particular probe. It will be necessary to search out sets of radials which cross in space, thus fixing the location of individual objects. Searching all the possible combinations systematically will require considerable computer effort, and ambiguities may persist. Gravitational ranging may contribute preliminary range estimates to aid the sorting algorithm, but a period of several minutes would be required to observe the curvature of the trajectories before ranges can be estimated with any accuracy.

By extrapolating forward in time from the current position and velocity of each object, the system can calculate its impact point. The cross-range error of such an estimate can be quite small, because it does not depend heavily on the inferred ranges. The down-range error is significantly larger, first because it is very dependent on the inferred ranges (with their larger errors), and second because the RV approaches its ground target at an angle of about 23 degrees to the horizontal, thus magnifying the range errors. One may conjecture that the cross-range error for impact point prediction can be reduced to about 100 meters, while the down-range error may be about 500 meters.

In addition to extrapolating forward from the probe observations, the system may also extrapolate backwards. Even though the extrapolation interval is larger than for impact point prediction, the observation accuracies suggested above may make it possible for the system to determine how each individual object was deployed from its MIRV bus. It is not clear whether this information would be useful to the defense, but it may aid the system in discriminating between RVs and decoys, or it may limit the offense's range of tactics.

Impact point prediction of this accuracy enforces a major constraint on the offense: In order to be convincing, the decoys must be aimed accurately at defended targets. Deploying each true RV requires repositioning the MIRV bus, so the offense must allow sufficient fuel and time for each such maneuver. Since the offense must deploy several decoys for each true RV, separately targeting each decoy becomes prohibitively expensive. Therefore, the offense is likely to deploy with each true RV a package of decoys which travel ballistically in echelon around it. The decoys must be spaced closely enough so that each realistically threatens the target, yet far enough apart so that it would be impossible to destroy more than one object (RV or decoy) with one KV. Consequently, the defense confronts many clusters of objects, each cluster typically including one RV and several decoys. These clusters, called closely-spaced objects or CSOs, are dense enough that they may not be resolved into separate objects when they are first detected by the probe at long range. The defense must detect these clusters, track them initially as unresolved images, resolve them into individual objects as they approach, and finally select which objects to attack as presumed RVs.

Impact point prediction, and discrimination and preferential defense insofar as they depend on it, would be compromised if the attacking RVs can maneuver after they are tracked. Then the defense could not assume that an RV was aimed at a target it was approaching ballistically. Discrimination by impact point prediction would be risky because an RV which appeared likely to miss its target might later maneuver to hit it. Preferential defense would also be risky because an RV approaching a target the defense is willing to sacrifice might maneuver to hit a defended target. The spacing of targets is critical in this context, because the range of maneuverability is certain to be limited. Thus closely spaced silos would allow easy re-targeting, but the 10 kilometer spacing of the Minuteman silos makes re-targeting a more questionable tactic for the offense.

The US has already conducted several programs to develop maneuvering RVs. Some of these were specifically intended to overcome BMD systems. The British recently revealed the Chevaline re-entry system which is intended to enable British Polaris warheads to penetrate the ABM system protecting Moscow.

Whether the RVs maneuver aerodynamically during re-entry, or whether they are equipped with with small jets for maneuvering just before re-entry, maneuverability will probably exact a large weight penalty on the RV design. Consequently, the offense is not likely to resort to maneuvering RVs unless they promise to accomplish a specific mission, such as overcoming a particular BMD system. On the other hand, the designer of a defense system must ensure that it cannot easily be neutralized if the offense consequently chooses to deploy maneuvering RVs.

The offense may choose to develop an alternative decoy strategy. Each decoy might be equipped with a small maneuvering rocket and a simple guidance system. After it is dispensed from the decoy package accompanying each RV, the individual decoy would place itself on a slightly different course to a different target according to programmed instructions. Of course, the decoy guidance could not be as accurate as the guidance of the MIRV bus which aims the real RVs. If the RVs were aimed at targets several hundred miles apart, the decoys could not be aimed accurately at separate targets. However, if the RVs were aimed at ICBM silos only a few miles apart, only a small increment of velocity need be applied to the decoys and therefore only modest accuracy is required of the decoy guidance to threaten other silos convincingly. Perhaps not all decoys would be accurately positioned, but the offense might be willing to allow the defense to discriminate against some decoys on the basis of impact point prediction if the corresponding relaxation of guidance requirements would simplify decoy design.

If the offense repositioned decoys immediately after they were dispensed by the RV, the defense (as noted earlier) might be able to reconstruct the deployment by backward extrapolation of tracking data and use this information for discrimination. However, the decoys may reposition themselves at any time during the interval from their deployment until they can be seen by the defense's sensors, although decoy guidance will tend to drift with delay. It is therefore likely that if the offense found it necessary to do so, it could confound the defense's efforts to reconstruct decoy deployment.

4) Discrimination. The RVs will almost certainly be accompanied by a variety of penetration aids in large numbers. To avoid exhausting the supply of kill vehicles on inert targets, the defense system must be able to distinguish RVs from decoys. Decoy design is a compromise between utility in

penetrating the defense and the weight penalty imposed by the decoys (and other penetration aids). To be useful, decoys must be much lighter than the RVs they imitate, although successful decoys are worth a considerable sacrifice in RV payload. As an example for perspective, if a typical RV weighs about 1000 kilograms, the offense may consider it worthwhile to employ several decoys per RV, each weighing about 10 kg.

Decoys are useful to the offense only if it is easier to deploy more decoys than it is for the defense to deploy more KVs. Although this is likely always to be true, if the defense could design a very light, very inexpensive kill vehicle, then the offense's decoy strategy could be outflanked.

The current basis for discrimination is the anticipated difference in infrared emission between RVs and decoys. (Discrimination by other means, such as radar or lasers, may be precluded given the long ranges of an exo engagement.) For thermal discrimination, an observer uses measurements of an object's radiation at several wavelengths to infer an object's temperature, and then uses variations in temperature to infer the object's mass. In principle, a lightweight decoy will show rapid variations in its thermal radiations while a massive RV will show recognizably more stability.

A key to understanding the basis of thermal discrimination is the concept of thermal inertia, an obvious analogy with the concept of physical inertia. According to Newton's First Law of Motion, an object at rest tends to stay at rest while an object in motion tends to remain in motion; this is the principle of inertia. Newton's Second Law of Motion states that the more massive an object, the more force is required to modify its motion. Therefore, an object's mass is an exact measure of its inertia, and vice versa. In an analogous way, the heat capacity of an object (its thermal mass) is a measure of the amount of thermal energy needed to change its temperature (its thermal inertia). Thermally massive objects tend to take longer to heat or cool to match their surroundings. It is reasonable to suppose that thermal mass is correlated with physical mass, but the correlation is poor. For example, a given volume of metal has a much greater physical mass but much less heat capacity than an equivalent volume of water.

Objects in space exchange heat with their surroundings by thermal radiation, and the radiation from an object can be observed and interpreted as a measure of the object's temperature. Warm objects tend to radiate more rapidly and at shorter wavelengths than cool objects. Here again, however, the correlation is not exact, but depends on the nature of the object's surface.

In the official exo scenario, the exo system would make observations at three wavelengths. BMD proponents[11] assert that a three-band temperature measuring scheme is immune from deception. It is further asserted that decoy designs have already been tested and shown to be ineffective against the discrimination algorithms developed for exo defense. No details of either the decoy designs or the discrimination algorithms have been given publicly, however.

It should be remembered that not only will the decoy imitate the RV, but the RV will also be re-designed so that the two are mutually imitative. Naturally, the specific function of the RV cannot be compromised by this re-design. On the other hand, there is no point in insisting on an ideal RV if it can easily be detected and destroyed by the defense. The offense will therefore design the decoys and modify the RVs to optimize the attack with respect to its overall performance against the defended targets, taking into account the need to foil the defense's discrimination.

The physical principles on which thermal discrimination is based are described in most elementary physics textbooks. Important considerations for successful discrimination are: 1) the thermal emissions of the attacking objects; 2) the observations made by the defense; 3) competing sources of infrared radiation; and 4) the likely deception techniques the offense may use against the defense.

The defense will attempt to discriminate between RVs and decoys by observing the response of these objects to transients in their surroundings. Presumably, the lighter decoys will approach equilibrium more quickly than the more massive RVs. Two such transients are important: first, the launch of the objects from the ambient temperature of the ICBM silos to their equilibrium temperature in near-earth space, and second, the transit into or out of the earth's shadow which may occur at some point in a polar trajectory. The first transient is unavoidable, but its effects may be minimized by designing both RVs and decoys to be in radiational equilibrium with their near-earth surroundings at a temperature of about $300^{\circ}K$. In any case, this transient takes place early in the flight of the attacking objects, leaving a period of perhaps 15-20 minutes for RVs and decoys to approach equilibrium before they can be observed by the defense. The transit of the earth's limb depends on both the time of day and the season of the year. The transit, if it occurs, could be in either direction, from sunlight to shadow or from shadow to sunlight. Ideally, from the defense point of view, the transit would take place while the defense can observe it, thus maximizing transient effects for discrimination. The offense, depending on the circumstances of the attack, may have the option of scheduling the attack to avoid offering this advantage to the defense.

Less pronounced transients would be caused by changes in the radiation from the earth below as the objects pass over land masses, the polar ice cap, clouds, etc.

The thermal emission from an object is governed by Planck's blackbody radiation law. Typical blackbody radiation curves are illustrated in the accompanying figure. They indicate that thermal emission peaks at a certain wavelength which decreases as the temperature is increased, according to Wien's displacement law:

$$\lambda_{max} T = 2.9 \times 10^{-3} \text{ m K}^{\circ}$$

For a temperature of 300^{0}K, the emission peak occurs at about $\lambda =$ 10 micrometers. If an object is viewed at two separate wavelengths straddling this peak, temperature variations could be detected by observing the ratio of the emissions in the two bands.

The accompanying table illustrates the variation in emission observed at three representative wavelengths for various temperatures. The most notable effect as temperature increases is that emissions at all wavelengths increase. To this extent, the increasing intensity from an object as it approaches an observer is equivalent in effect to increasing temperature. However, the emission at the short wavelength increases most sharply as a consequence of the displacement law (as indicated by the column of ratios in the table), thus making temperature measurements possible.

The objects in fact are not true blackbodies, but have a finite emittance which is in general a function of wavelength $0 \leq \epsilon(\lambda) \leq 1$. Very importantly,

Figure 2 - Blackbody Curves (Spectral Radiant Exitance) for Typical Exoatmospheric RV Temperatures

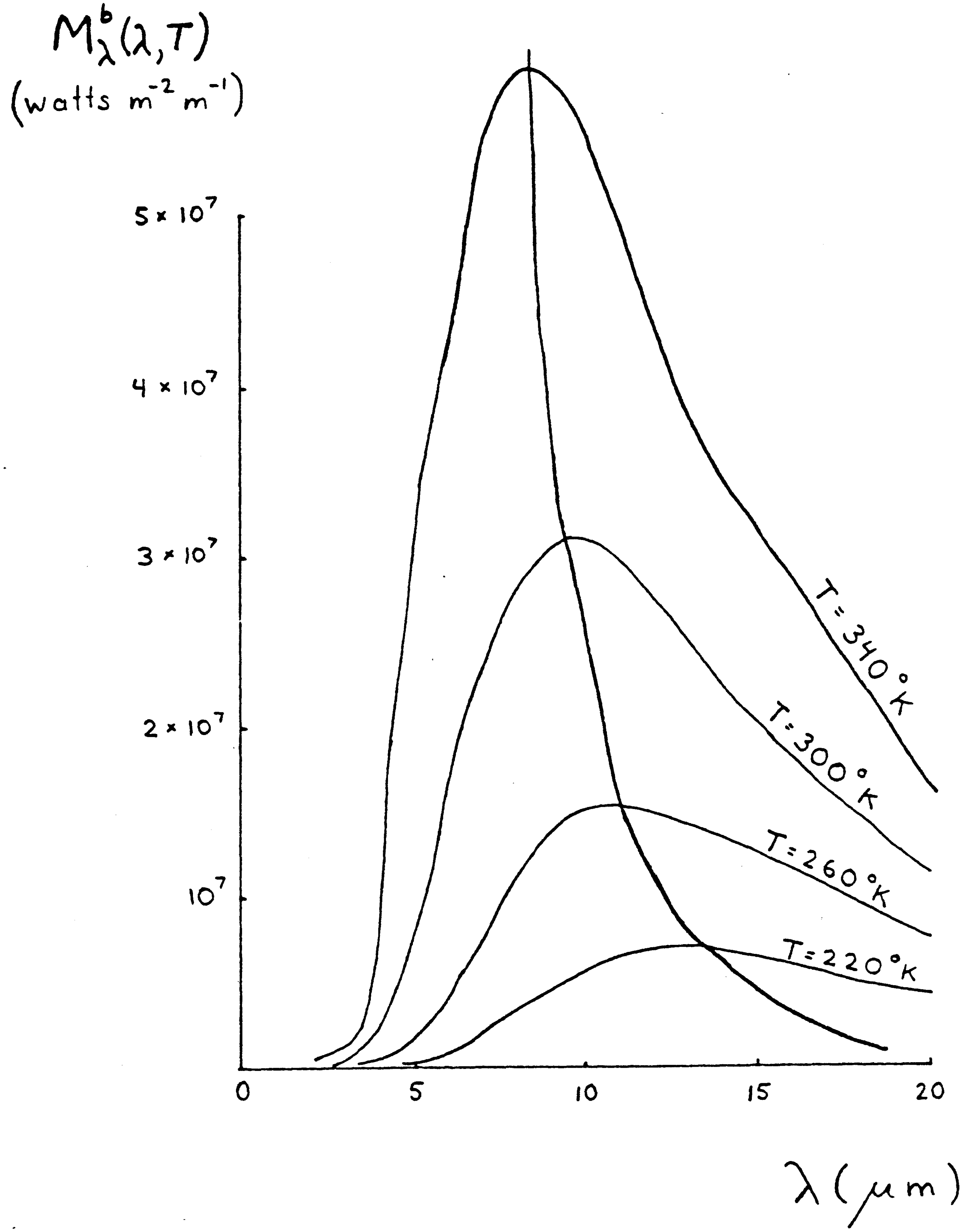


Table 1 - Blackbody Brightness for Several Temperatures and Wavelengths (Spectral Radiant Exitance in watts/($m^{-2} \cdot m^{-1}$))

Wavelength (μm) T(^{o}K)	8	12	16	8/16
220	3.2×10^{6}	7.0×10^{6}	6.1×10^{6}	0.53
240	6.4×10^{6}	1.0×10^{7}	8.6×10^{6}	0.74
260	1.1×10^{7}	1.5×10^{7}	1.2×10^{7}	0.98
280	1.9×10^{7}	2.1×10^{7}	1.5×10^{7}	1.24
300	2.9×10^{7}	2.8×10^{7}	1.9×10^{7}	1.52
320	4.2×10^{7}	3.6×10^{7}	2.3×10^{7}	1.82
340	5.8×10^{7}	4.6×10^{7}	2.7×10^{7}	2.12
360	7.9×10^{7}	5.6×10^{7}	3.2×10^{7}	2.45
380	1.0×10^{8}	6.7×10^{7}	3.7×10^{7}	2.74

the emittance $\epsilon(\lambda)$ has a complementary relationship with the reflectance $\alpha(\lambda)$, so that high emittance implies low reflectivity and vice versa.

The intensity of the radiation diminishes with distance according to the inverse square law. Further, the total power reaching the detector is limited by the aperture of the observing telescope. For an object of radius 1/2 meter and temperature 300^{o}K, viewed at a distance of 1000 km by a telescope with an aperture of 1/2 meter, the power in a bandwidth of 1 micrometer centered at 10 micrometers is:

$$P = P(\lambda)\Delta\lambda = 4.9 \times 10^{-14} \epsilon \, W_{\lambda = 10\mu m}(T = 300^{\circ}K) \times 10^{-6}$$

$$= 1.5 \times 10^{-12} \epsilon \text{ watts}$$

The measurement of such small powers is complicated by thermal noise, particularly that developed within the detector itself. Consequently, the detectors must be cooled. The mercury-cadmium telluride detectors likely to used for the two shorter wavelengths must be cooled to about 77^{o}K (liquid nitrogen), while the extrinsic silicon detector likely to be necessary for the longest wavelength must be cooled below 10^{o}K (approaching the temperature of liquid helium). In order to be ready for immediate launch and operation, the detectors must be maintained continuously at these temperatures. In all likelihood, this can be accomplished by large refrigeration systems on the ground, with reservoirs of liquid nitrogen and liquid helium carried aboard the spacecraft for its short flight.

To carry out discrimination, the detectors must be calibrated for absolute intensity measurements. This poses significant difficulties particularly for imaging sensors with multiple detectors in an array. Current fabrication techniques for imaging arrays cannot ensure uniformity of performance among the individual detectors; the variations in detector response are often called "fixed pattern noise". As the image of an object traverses the array, these variations cause apparent fluctuations in the detected intensity, thus obscuring the information needed for discrimination. This error source can be compensated by the data reduction algorithms supporting the sensor, but only if the system is painstakingly calibrated. Unfortunately, such calibrations are easily disrupted by external influences, most importantly, by nuclear radiation.

In addition to generating its own thermal radiation, an object which is not a true blackbody tends to reflect radiation from other sources, because, as noted, emittance and absorptance are complementary. Most important of the reflection sources is the earth, which also has an effective temperature of about 300^{o}K and which fills almost half the sky. The sun is another important source, but because of its distance it contributes relatively little intensity in the far infrared. Rather, the sun's much stronger intensity at shorter wavelengths tends to be absorbed by an object and re-radiated at longer wavelengths.

The combination of long wavelength, limited telescope aperture, and long observing distance means that an individual object the size of an RV will almost certainly be unresolved by the defense's optical system. That is, diffraction will make all the radiation from the object appear to come from a single point source. For example, if an RV has an effective diameter of one meter, and the probe has a telescope aperture of 1/2 meter operating at 10 micrometers, the RV is unresolved at ranges beyond about 50 kilometers. The situation naturally becomes worse at longer wavelengths. It is unlikely that the probes will ever be this close to any of the RVs. If the interceptor carries a telescope, it is likely to be smaller, perhaps with an aperture of about 0.1 meter, reducing the range for resolution to about 10 kilometers. Since the RV and the interceptor are approaching each other at almost 10 km/sec, this would allow the interceptor about one second after resolving an RV to complete its mission, that is, to observe the object, decide that is an RV, and maneuver to intercept it. Since this is clearly impractical, the defense must base its discrimination on observations of unresolved objects. The offense thus has the opportunity to combine several indistinguishable sources of radiation on the surface of the attacking objects (RVs and decoys) in order to confuse the defense. Put another way, the offense has many degrees of freedom which can be adjusted independently to construct a specified net emission for three observed wavebands.

Another consequence of the poor resolution of the infrared optical telescopes is that the attacking objects can hardly be seen at all against the earth background. At a range of 1000 kilometers, the probe's telescope could resolve an area about 20 meters across. An RV about a meter across would take up only a small fraction of this area. If the RV is projected against an earth's background at a similar effective temperature, detection, let alone discrimination, becomes virtually impossible.

While the defense is attempting to separate the RVs from the decoys, the offense attempts to confuse the two. Passive infrared discrimination is based on the assumption that the surface emissions of an object betray its contents, a statement which implicitly suggests the techniques available to the offense to foil infrared discrimination:

1) insulation;

2) passive surface equilibrium;

3) surface heating;

4) reflection;

5) noise.

Insulation enables the offense to isolate the surface of an object from its interior. Although there may be other ways to do this, the most elegant insulation so far proposed is the Garwin thermos, suggested by Richard Garwin, a familiar and pungent commentator on BMD systems and policy. Garwin's idea is that both RVs and decoys could be enveloped by balloons made of aluminized mylar. These would be inflated shortly after the objects were deployed above the atmosphere. The aluminum coatings on the balloon and the object would inhibit radiation exchange between the two, while the vacuum of space would conveniently suppress thermal conduction.

Having insulated the surfaces of the object from its interior, the offense can design each surface to be near radiational equilibrium with its environment. Surfaces are always exchanging radiation with other surfaces around them; in the present case the attacking objects are exchanging radiation with the earth and the sun, and with the relatively cold background of outer space. The rates of emission and absorption depend on the environment and on the emittance of the surface (which is equal to the absorptance at any given wavelength). If emission exceeds absorption, the object tends to cool until the two balance; similarly, if absorption exceeds emission, the object warms until equilibrium is reached. By adjusting emittance and absorptance, the object can be designed to maintain a specified equilibrium temperature in a given environment. The offense could design both the RVs and the decoys to be in equilibrium at similar temperatures corresponding to the effective temperature of the earth. This choice would minimize the thermal transient which occurs when these objects are launched, and also camouflage the objects whenever they are viewed against an earth background.

Techniques for maintaining thermal equilibrium in space are not at all new; in fact, they are as old as the space age itself. The need to maintain thermal stability in satellites or in deep space probes has engendered a sophisticated technology for thermal maintenance.[12] A standard technique is to use patterns of special paints. Various paints have different specified emissivities at different wavelengths. The paint patterns chosen would absorb solar radiation and emit $300^{\circ}K$ blackbody radiation at predetermined rates, allowing predictable passive control of temperatures without a significant weight penalty. An established elaboration of this technique is to adjust the effective emittance in flight using louvres and a straightforward thermostatic system.

Simple electric heaters (or even catalytic burners of oxygen and hydrogen) could be used to maintain sections of the object's surface at preselected temperatures. The power requirements for such devices need not be large. Even if the object were a true blackbody radiating into empty space, less than 500 watts of power would be required to maintain its temperature. Much less power would be required if the surface of the object were designed to be almost in equilibrium with its near-earth surroundings at the specified temperature. Since it is easier to heat the surface than to cool it, the designer would aim for an equilibrium temperature slightly lower than the specified temperature and then use the heater to raise the temperature as necessary. Because the insulated surface would have low thermal mass, it could respond very rapidly to controlled adjustments of temperature.

As noted earlier, emittance and reflectance are complementary to each other. By making the object's surfaces reflective, the offense disguises the object's contents while it camouflages the object with the radiation of its surroundings. The earth of course is the principal source of camouflaging radiation, since it fills almost half the sky.

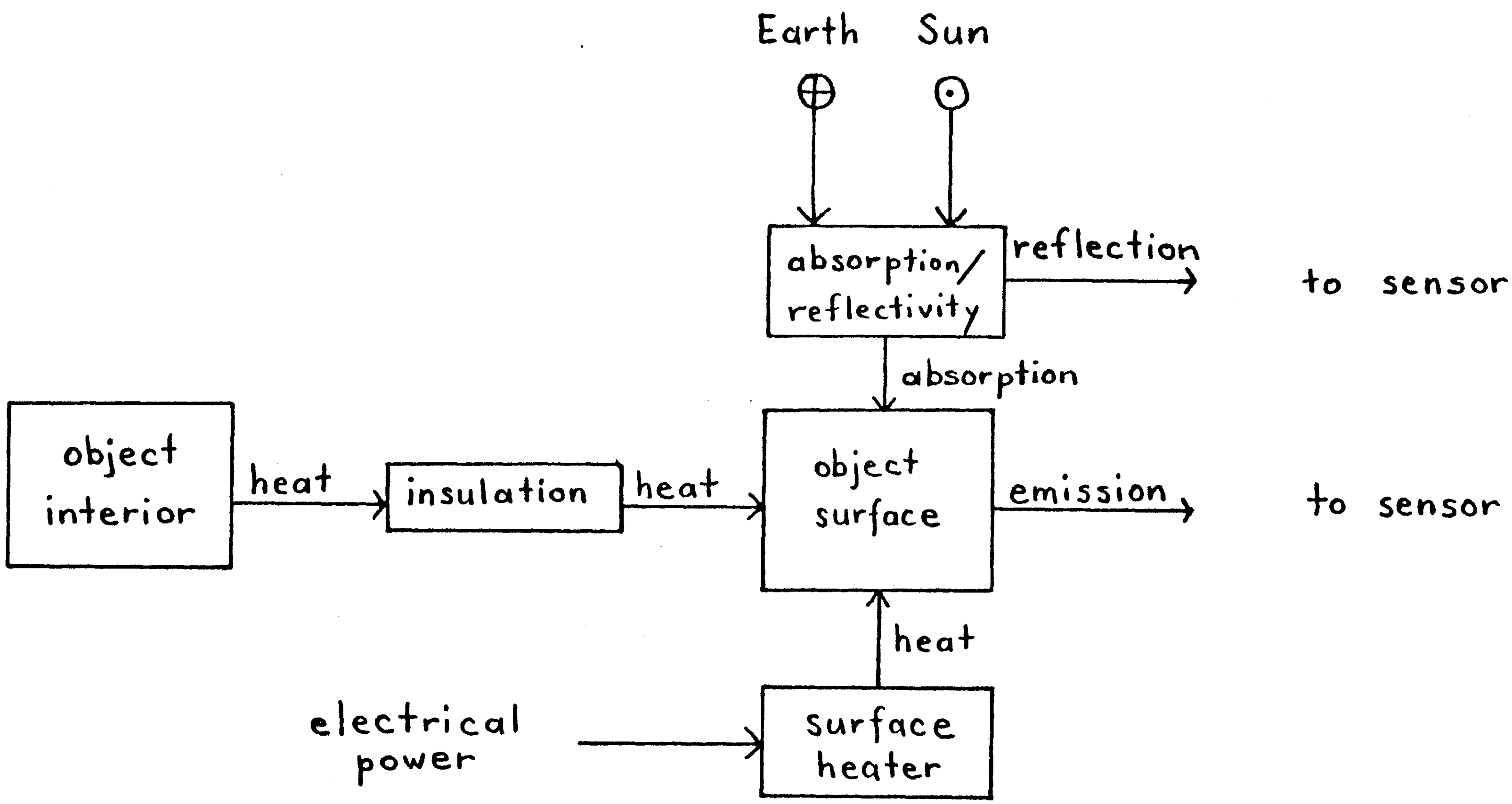
Finally, the offense may attempt to confuse the defense's sensors by dispensing other small radiation sources around the attacking objects. These are called "aerosol" and are somewhat analogous to the aluminum chaff used to confuse radar. Since the attacking objects are so poorly resolved by the defense's optics, the offense could easily surround the objects with a variety of radiation noisemakers which through both emission and reflection would fill the discriminating detector with extraneous confusing signals. Further, if discrimination depended on variations of infrared radiation as a function of time, the aerosol objects could be made asymmetric and allowed to tumble in their trajectories, providing a time-varying random noise source. One might guess that these objects would be somewhat like ping-pong balls, hollow and light-weight. Possibly the offense would use much finer aerosol, comparable in size to the infrared wavelengths used by the detectors in order to scatter light most effectively. However, the only effective source of light for scattering is the earth; sunlight is not very intense at these wavelengths. Further, true scattering contributes a degree of polarization to the scattered light which might aid the defense in suppressing its effects. A more efficient technique would be to dispense aerosol objects which absorb sunlight at visual wavelengths and then re-emit the energy thermally at the necessary long wavelengths.

All of these techniques can be combined to produce a specified output in each of the three wavebands for either an RV or a decoy. Because the defense's optical instruments are unable to resolve an attacking object, the offense can design the object so that the radiation from several separate sections of its surface combine to produce an appropriate level of radiation in each of the three discrimination wavebands. This ability to adjust the radiation from each section independently, as long as the total radiation meets specifications, gives the offense extra latitude in designing anti-discrimination techniques.

A diagrammatic representation of this combination is shown in the figure. The interior of the object, which may itself contain several regions at different temperatures, communicates with each external surface through an insulating layer. Each surface is characterized by its emittance and complementary reflectance in each of the three wavebands. The temperature at each surface can be sensed and adjusted as necessary to satisfy thermal emission requirements. The sun provides some reflected radiation, but contributes to thermal equilibrium mostly through absorption at shorter wavelengths. The earth at an effective temperature comparable to the surface (at each waveband) provides radiation which is both reflected and absorbed. A microprocessor controller (with sensors to detect external conditions) can quickly adjust the radiation emitted by the object as a whole.

5) Tracking and Discrimination Combined: The Forward Acquisition System. Because the time available to conduct the defense is so small, tracking and probably discrimination must be performed by a system component separate from the interceptors, generically called the forward acquisition system. In the

Figure 3 - Thermal Emission Control for RVs and Decoys



scenario described earlier, this task was accomplished by the probes in ballistic trajectories. Alternatively, these functions might be performed from a high altitude aircraft flying in northern latitudes, or from satellites.

On present evidence, lofted optical probes appear to be the most likely candidate for the forward acquisition role. Launched in response to an early warning message, they carry out an assessment of the attack before the interceptors are launched. They perform most of the tracking required by the system and at least some of the discrimination between RVs and decoys. Observations of most of the attack complex from a high altitude limits the offense's chances to nullify preferential defense, while extrapolation of the attack trajectories both forward for impact point prediction and backward for reconstructing MIRV bus deployments further constrains the offense's tactics.

The optical sensor technology for the probe has already been tested partially. Four flights of an experiment called the Designating Optical Tracker[13] (Boeing and Hughes) have been launched from Kwajalein Atoll to view Minuteman RVs launched from Vandenberg Air Force Base. A similar sensing system, the Homing Overlay Experiment (Lockheed) has begun flight testing.

Official descriptions of the exo system suggest that the probe is launched almost vertically into a trajectory which keeps it aloft for about 20 minutes. Such a trajectory would have a maximum altitude of about 2000 km, and would require an effective launch velocity of about 5.5 km/sec.

A critical requirement for the probe is that it be able to observe the attacking objects clearly against the cold background of the sky. Seen against an earth background, the objects are much more difficult to detect because they are likely to have temperatures and therefore brightnesses comparable to the earth's background. Tracking would then be difficult and meaningful discrimination impossible.

If the probes observe the attacking objects from an altitude greater than the objects themselves, then as the objects approach they will at some time dip below the limb of the earth and therefore be observed against the earth's background. There is thus a minimum distance for successful observation of the objects by the probes. This distance is dependent on the altitudes of the objects and probes, and is likely to be greater than 1000 km. This minimum range is dictated by two considerations: first, the probe spends most of its 20 minutes aloft at altitudes greater than 1000 km, well above the incoming RVs, and second, if the probe is launched within a few minutes of the arrival of the attacking objects, it will still be ascending as the objects are approaching and descending.

In one respect, a minimum range of 1000 km is not a disadvantage. At this range the objects are only about 150 seconds from their impact points, leaving just enough time for the interceptors to be launched for intercepts above the atmosphere. This consideration would be voided if the probe could continue its observations and transmit data to the interceptor after the interceptor is launched towards the RVs.

The offense can exacerbate the minimum distance problem for the defense by using depressed trajectories for its RVs[14]. Usually, the offense would choose to fire each missile payload so that the RVs follow trajectories which minimize the kinetic energy required for ballistic flight from the launch point to the targets. However, by sacrificing a fraction of the payload, the offense can employ non-optimum trajectories which are considerably closer to the earth's surface. The geometry of the situation is such that only a small depression of the trajectory will result in a large increase in the minimum range for observation. ICBM boosters are usually designed with a significant margin of boost capacity which for most missions must be wasted, in some sense. It is therefore likely that depressed trajectories could be accommodated with relatively little loss of payload capacity. Nevertheless, depressed trajectories have other drawbacks, including a tendency to decrease the accuracy of the RVs due to increased errors during re-entry. It is possible that the offense would choose low trajectories for RVs in an early attack wave, hoping that these RVs might penetrate to suppress the defense before the remaining RVs arrive to destroy the ICBM silos.

As noted earlier, the infrared optical telescope is likely to have an aperture of about 1/2 meter diameter, which at a wavelength of 10 micrometers gives the telescope a diffraction-limited resolution of about 20 microradians (20 meters at 1000 kilometers). In effect, this resolution limit determines the smallest practical unit of angle which can be measured by the optical system. If each optical resolution element corresponds to one pixel (or separate picture element) in the solid-state focal plane array, an effective focal length of 5 meters (obtained using folded reflective optics) provides a practical pixel spacing of 100 micrometers.

The angular domain which the probe must patrol is huge when measured in terms of the number of pixels required. The attacking RVs can approach the US from a 40^{o} range of azimuths and may be viewed over a vertical range of at least 10^{o} above the earth's limb. At 20 microradians/pixel, this is an angular domain of 35,000 x 9000 pixels. Of course, if the probe continues to observe the RVs as they approach and pass abreast, an even larger observing domain will be required.

Because such a large domain cannot be observed continuously, the telescope must scan its patrol domain. It is possible to design telescopes with a rectangular field of view as large as 10^{o} in one dimension, so it might not be necessary to scan in the vertical dimension. This of course implies a focal plane array about 9000 pixels high (almost a meter), a goal which may not be achievable. To increase the total observing time, the scanning array might be 10-100 pixels wide. As the image of an object is scanned from one column of pixels to the next, electronic logic would transfer the accumulated signal in step with it. Even with the advantage of this time delay and integration (TDI), the total amount of time that any one object could be viewed is small. For example, if the scanning array is as large as 100 pixels wide and must scan over 35,000 pixels, each object can be viewed only 1/350th of the time. If the probe can view an object over an interval of 4 minutes, each object is effectively observed for only about 1/2 second. If the probe completes a scan every 20 seconds, there is thus time for 12 scans of about 0.05 seconds each.

An alternative to launching the probes vertically is to launch them on northward ballistic trajectories into the path of the attacking objects. While these trajectories allow the probe to come arbitrarily close to the objects and to view them against the sky, they have several potential disadvantages. First, a close approach may make the probe more vulnerable to offensive countermeasures. Second, by increasing the closing speed between probes and RVs, it somewhat shortens the interval during which observations can be made, from about 4-1/2 minutes to about 2-1/2 minutes. Third, from a lower altitude an individual probe will be able to observe a smaller fraction of the overall attack, thus tempting the offense to expand its options for overcoming preferential defense. Fourth, the sensor may require a wider field of view to track the attacking targets as they approach the probe. Nevertheless, by launching several probes into different trajectories, none too close to the attackers, it should be possible to overcome all these objections.

Rather than launch the probes in response to an attack, another possibility is to maintain them in orbit constantly. A probe in low orbit could view the attack from a fixed altitude much lower than that of the lofted probe, thus making it easier to view the attack against a sky background.

However, such a deployment would suffer the same disadvantages that plague all strategic systems based on satellites in low orbit.[15] In order to ensure that several probes were in position over the US at the moment they were needed to view an attack, several hundred probes must be maintained in orbit with the expectation that most of them would be out of position in other parts of their orbits at the critical moment. Since the probes are sophisticated and expensive components of exo defense, the cost of maintaining this large fleet may be prohibitive. Further, having the probes in orbit leaves them vulnerable to possible Soviet attacks which of course could be timed to embarrass the defense at a critical moment.

Maintaining the probes in orbit involves at least one special technical problem. The IR sensors aboard the probe must be maintained at very low temperatures in order to avoid overwhelming them with their own thermal noise. If the probes are ground-based, the sensors can be maintained at these low temperatures (about 10°K) by external refrigeration equipment. For the short period after launch when the sensors are in operation, they can be cooled (to about 4°K) by a small portable reservoir of liquid helium.

However, state-of-the-art refrigeration systems which can maintain $10^{o}K$ are quite heavy. They require mechanical compressors with special problems of lubrication. With present technology, it is difficult to imagine such a refrigeration system operating for years without maintainance, as would be required for a satellite. Portable refrigeration systems capable of liquid helium temperatures are far more problematical. However, long-term cryogenic cooling is a requirement shared by many civilian and military programs. Recent reports suggest that new techniques may become available during the next decade to satisfy this requirement.[16]

In yet another alternative, forward acquisition might be carried out from high-altitude aircraft instead of space vehicles. In this case, the sensors would be above most but not all of the atmosphere, which would be a source of absorption and noise. Further, aircraft would probably have to be maintained continuously on station because there would be too little time available after an alert for an aircraft to take off and reach operating altitude. The cost of maintaining aircraft continuously aloft might be prohibitive even if aircraft could perform the forward acquisition role acceptably.

While the optical probe is necessary to carry out tracking, in view of the foregoing it is very hard to believe that the probe could successfully perform discrimination. It is obvious that discrimination is the most demanding problem for exo BMD, and the probe operates over too great a distance for too short an effective period of time for discrimination against a sophisticated attack to be credible. The task of discrimination must therefore be forced onto the interceptor, or even onto the KVs themselves. The role of the probes in providing timely data for an orderly defense would then be severely compromised, offering the offense opportunities for suppressing the defense. For example, the offense could launch a barrage of decoys, forcing the defense to commit its interceptors uselessly before the main attack by real RVs.

If such complications could be circumvented, then there may be some advantage in reserving the discrimination function for the interceptors. The probes can be that much simpler and the interceptors can approach much more closely before committing the system to discrimination decisions. Further, the inteceptors may even approach close enough to allow active means of discrimination, such as radar or laser reflection, although what technical basis would be used for active discrimination is not obvious. However, the cost is high. Having to reproduce sophisticated sensor and computer hardware for each interceptor (or KV) clearly adds to the weight of the interceptor payload and to the overall expense of the exo system.

6) Multiple kill vehicles. Since each ICBM can carry several RVs, it would require several simple interceptors to defend against one ICBM. Each interceptor would require a complete booster rocket with all its ancillary equipment (such as launch facilities and guidance), thus making it expensive to offset one MIRVed ICBM with multiple interceptors. In fact, MIRVs were developed originally as a means for saturating ABM systems. To offset the advantage of MIRVs, it is necessary for each interceptor to kill several RVs. For a system using non-nuclear kill, this means that each interceptor must carry several independent kill vehicles, in effect "fighting MIRV with MIRV."

Two separate development programs for kill vehicles have been supported by the Army BMD program.[17] The first KV, called the HIT (Homing Interceptor Technology) vehicle was developed by Vought. It is designed to home on its target and destroy it by direct impact. The original HIT vehicle was designed to weigh only 15 pounds and to be very inexpensive. Such KVs might be deployed freely against both RVs and decoys with little regard for accurate discrimination. A different version is being developed as the Air Force anti-satellite weapon, to be launched from an F-15 aircraft. This version has become much heavier and far more expensive than the original HIT vehicle was intended to be. A more recent KV, called the HOE (Homing Overlay Experiment) vehicle has been developed by Lockheed. It is estimated to weigh several hundred pounds and destroys its target by scattering shrapnel in its path.

The interceptor might deploy its KVs either simultaneously or in sequence. If each KV can be assigned its target simultaneously by data transfer before it is deployed, all the KVs may be deployed almost immediately as soon as the interceptor is clear of the atmosphere. If, on the other hand, the interceptor must maneuver to acquire each new target and direct the KV toward it, then the KVs must be deployed sequentially. Sequential deployment of KVs may impose constraints on the inteceptor's deployment schedule.

In many defensive situations, it is desirable to have some method of verifying that a successful kill has been made so that the defense system can be re-directed against other adversaries. Such kill verification criteria probably will be superfluous for exo BMD. Within the time constraints imposed on the exo system, there would probably be too little time to deploy a second exo kill vehicle against an RV after an initial attack even if it was known to fail.

Some doubt has been expressed that an RV can be reliably destroyed by collision because the thermonuclear weapons in ballistic missile RVs are said to be quite robust and difficult to disrupt. On the other hand, because the

RV decelerates extremely violently during re-entry, the integrity of its heat shield is crucial to its survival or at least to its accuracy on target. A collision between the RV and even a small object at closing speeds of 9-10 km/sec should be devastating. Any damage to the RV, even if it were not detectable before re-entry, would almost certainly cause the RV to break up or to deviate obviously from its course during re-entry. Survival of the RV during re-entry is therefore a credible negative criterion for kill. If an endo system were deployed in support of the exo system, one could reliably assume the viability of any RV surviving re-entry on target.

The homing accuracy required of these kill vehicles is unprecedented in BMD applications, so uncertainty must exist about its reliability. Fortunately, both the HIT and the HOE vehicles will soon be tested in realistic settings. Prototypes of the HIT vehicle have already been tested in laboratory conditions. In addition, the Air Force is developing a variant of the HIT vehicle as an anti-satellite weapon to be launched from an F-15 aircraft. This system may be tested against satellites in the near future. The HOE vehicle is due to be tested against Minuteman re-entry vehicles over the Pacific. In short, indicative tests of non-nuclear kill should take place in the near future.

The booster carrying the kill vehicles must be adequate to loft the KVs above the atmosphere into the paths of the incoming RVs. The Spartan interceptor of the Sentinel and Safeguard programs is a suggestive antecedent. It could reach a height of about 950 km or a ground range of about 950 km, and it defended a roughly circular area of somewhat smaller radius. From this evidence one may infer that the Spartan rocket generated kinetic energy equivalent to about 2.5 km/sec at ground level. If this velocity were generated instantaneously at ground level, the Spartan would require about 45 seconds to climb straight up to an altitude of 100 km. A Spartan with finite acceleration on an inclined trajectory might require 60-75 seconds from launch until the kill vehicles were deployed. The RVs would traverse about 420-525 km in this interval, and would still be several hundred kilometers from their targets. Thus the interceptors must be launched while the RVs are still about 1000 km from their targets.

With an effective range of less than 950 km, each interceptor site could defend no more than one of the current Minuteman ICBM bases. Therefore, six separate sites would be needed to defend the Minuteman force completely, and additional sites might be needed to defend the MX bases if they were not collocated with the Minuteman bases.

The booster might be enlarged to achieve greater range and therefore greater coverage. To take advantage of the improved performance, the interceptors would have to be launched earlier with the RVs at greater ranges.

7) Computation and battle management. In a large attack, the defensive system would face perhaps 50,000 objects in ballistic trajectories, including RVs, decoys, and booster fragments. The computer for the system must be able to contend with a huge volume of data in real time. Extraneous objects such as booster debris or spent MIRV buses would have to be suppressed at an early stage of computation to avoid saturating the computer. Decoys must be separated from RVs according to sophisticated algorithms. Accurate tracking data must be computed and interceptor courses calculated.

The actual volume of computation required for BMD applications is difficult to assess, and is not in itself a critical issue in assessing exo

BMD. The question arises now because it was important in earlier ABM debates. The commercial computers available when Sentinel and Safeguard were designed were inadequate for the requirements of endoatmospheric defense in particular, in which an entire engagement may take place in an interval of about ten seconds. Exoatmospheric engagements would take place over periods of several minutes, and of course computer technology has advanced considerably over the last decade. More important than the mere volume of computation is the issue of reliability. Can the computational facilities of an exo system be distributed, protected, and maintained so that the system is always ready to manage a huge threat on short notice in spite of the offense's efforts to disrupt them?

The air traffic control computer network may serve as an example of an interconnected system demonstrating necessarily stringent reliability, but the parallel is questionable. Unlike BMD systems, the system has been exercised in realistic circumstances for years, so that idiosyncrasies have been identified and eliminated. Further, although computers are indispensible for normal operation of air traffic control, the system is ultimately under the supervision of knowledgeable human operators, who typically have time to recognize and compensate for system lapses if they occur.

There is of course a special requirement for mobile computers to support the optical sensors on the probe. However, the mobile computer almost certainly will not perform the role of Battle Manager executing strategy for the system as a whole. Rather, it is needed to reduce the huge volume of raw data produced by the sensors before that data is forwarded to the ground to be digested by the Battle Manager computer. Therefore, the mobile computer must be sized to achieve an optimal reduction of the flow of data between the probe and the ground. Transferring and preprocessing raw data from the optical sensors allows a high degree of parallelism which simplifies the task. This data compression role is relatively minor and may well be achievable with current technology.

Such sophisticated computers have large power requirements. For example, the Cray 1 or the Cyber 205 need about 100 kilowatts of power for operation of the central processor alone. Not only would the probe vehicle have to provide the necessary power over a period of several minutes, it would also have to dissipate the heat generated. A recirculating refrigeration system would be heavy, while a once-through cooling system would require a large reservoir of refrigerant which if discharged overboard would generate a large plume. A hazard for the probe already acknowledged is the possible contamination of its operating environment by unintended outgassing from the probe itself.[19]

To avoid these problems, BMD officials hope to use a cryogenic computer based on superconducting Josephson junctions. Several computer manufacturers (notably IBM) are intensively pursuing development of superconducting computers because they offer significant advantages in civilian applications, especially speed, compactness, and low power requirements. Nevertheless, progress is slow. Only simple superconducting computer circuits have been demonstrated to date, and small laboratory prototype computers are not anticipated before 1985. Large computers intended for mobile operation in hostile environments will not be available until years later.

8) Communications. Because the components and functions of the system must be distributed in various locations, reliable communications must be established among the components. Three generic types of communications may

be required, each with its own intrinsic vulnerabilities. Ground-to-ground links such as those for early warning might be physically destroyed. Space-to-ground links such as those from the probes to the Battle Manager might be disrupted for extended periods by nuclear explosions in the atmosphere. Space-to-space links, which may be required for direct communications among the probes and interceptors, also might be interrupted at least momentarily by nuclear explosions.

The assurance of reliable communications is essentially a straightforward engineering problem, to be solved using known techniques.[19] The most significant problem is the preservation of links between the probes and the Battle Manager through the atmosphere in spite of disruptions by nuclear detonations. A reduction of the volume of data to be transmitted through the use of data compression techniques aboard the mobile computer tends to ameliorate this problem. Nevertheless, the volume of data to be transmitted will be huge, straining communications even in benign circumstances. While the general principles of data transmission through a nuclear blackout are well understood, the Nuclear Test Ban Treaty precludes detailed testing of the transmission link and therefore enforces conservative design.

The most likely mode of communication through the atmosphere will be the EHF or SHF radio bands (0.1 - 10 cm). At these wavelengths, a small antenna can provide a narrow beam over a straight path, although the beam must be accurately steered. The narrow beam maximizes signal strength while it minimizes opportunities for enemy jamming. A high carrier frequency also offers higher data rates through larger bandwidths. Finally, the absorption of radio waves by plasmas induced by nuclear fireballs is less for higher frequencies, although the communications system must still be designed to avoid the effects of scintillation (phase shifts) caused by plasma turbulence.

IV. Anticipated Countermeasures

If the US chose to deploy an exoatmospheric BMD system, presumably the USSR would attempt to find ways to overcome it. Because the success of exo BMD depends so critically on the successful opertion of each of its components, the offense would obviously attack its weakest links. Offensive tactics might include:

1) Attacks on vulnerable system components, such as the early warning system, the probes, the interceptors, or the Battle Manager computer;
2) Pin-down attacks by ICBMs or SLBMs on the probes and interceptors;
3) Spoofing, to draw the defense into committing itself against a phony attack.

1) Attacks on vulnerable system components. As already noted, the early warning system must function in a timely fashion to initiate the operation of the BMD system. Some elements of the system, in particular the early warning radars, are placed in vulnerable locations which makes them likely targets for a sudden disruptive attack. As satellites become increasingly important for early warning, it is likely that they also will be threatened by new weapons. The USSR has shown considerable interest in anti-satellite weapons and has tested crude anti-satellite interceptors.

The probes are especially important and especially vulnerable components of exo BMD. In view of their complexity, it is likely that the system can include only a small number of probes relative to the number of interceptors. In order to perform their tasks of tracking and discrimination, the probes must be launched above the atmosphere toward the stream of attacking objects.

To disrupt the probes, the offense might replace some of its RVs with thermonuclear weapons designed to detonate near the probes. Above the atmosphere, the most important effects of a nuclear explosion would be soft x-radiation from the nuclear fireball, and neutrons and gamma radiation from the nuclear reactions. The x-rays can be stopped fairly easily by metallic shielding if it has sufficient heat capacity to withstand the energy absorbed. The gamma radiation may also be partly shielded, and its effects on the probe components may be less significant than those of the neutrons. High energy neutrons present the greatest threat because it is difficult to shield against them and because they are highly disruptive to solid state electronics. For this reason, a weapon to be used against the probes would be designed (much like the so-called neutron bomb) to produce a large yield of high energy neutrons from thermonuclear reactions.

Techniques for hardening electronics against nuclear radiation will of course be incorporated in the design of the probe to reduce its vulnerability, although they will increase its weight and complexity. The new technologies which may be included in the probe, such as solid state infrared detector arrays and cryogenic computers, may pose new problems for radiation hardening. The properties of the crystalline materials used in the detectors must be carefully optimized to achieve useful efficiency at such low photon energies, making them especially vulnerable to radiation. Even minor disruption of the detectors might disastrously alter their sensitivities, making it impossible for the probe to perform accurate discrimination.

An important mechanism for reducing the effects of nuclear radiation in solid-state electronics is the thermal annealing of the crystalline defects generated by radiation. This mechanism is highly temperature-dependent.

While it may be effective at ordinary temperatures, it will not be effective at the cryogenic temperatures in which the detectors and perhaps the mobile computer must operate.

It is difficult to assess quantitatively how completely the probe must be hardened, or how close a nuclear weapon must be detonated to disable it. Some impression may be gained from the example of a 1 MT exoatmospheric explosion. At a distance of 10 km, such an explosion would deliver roughly 80 cal/cm^2 in x-rays, 10^4 rads(Si) of gamma radiation, and 2×10^{13} neutrons/cm^2.[20] To survive these levels, strenuous hardening efforts would be required.

Rather than attempt to destroy the probe directly, the offense may choose to detonate warheads in the probe's field of view. Although the vulnerable detector arrays would be shielded from most of the radiation by baffling which takes advantage of the folded optical system, some of the infrared radiation in the passbands of the optical system will reach the detectors and may blind at least parts of the arrays.

It is even conceivable that the offense could place high energy lasers aboard the MIRV buses to incapacitate the probes as they approach the attacking objects. High energy carbon dioxide lasers are relatively compact and efficient, and their emission lies in the infrared where it might succeed in blinding the probe's sensors.

More importantly, the radiation from such detonations would excite large regions of the upper atmosphere, causing it to fluoresce for a considerable period. If this light is outside the field of view of the probe, careful optical design can prevent it from reaching the detector arrays. However, fluorescence in the field of view may mask the probe's view of the attacking objects. Sophisticated image processing algorithms can be expected to compensate partially for fluorescence which appears in the same picture elements as an attacking object, but the correction is likely to be imperfect. As always, the discrimination function is most sensitive to this additional disruption.

Fluorescence as a result of nuclear explosions is strongly dependent on altitude, and may not be a severe problem in viewing the attacking objects when they are far above the earth's limb. However, by carefully placing its nuclear precursors in the upper atmosphere behind the attacking objects along the probe's line of sight, the offense can raise the altitude at which the objects are masked by the earth's limb and therefore increase the minimum distance at which the probes can view the objects for tracking and discrimination.

The offense may also detonate nuclear precursors in the paths of the ascending interceptors and kill vehicles. Presumably, the precursor warheads would lead the attack wave, forcing the interceptors to pass through them to attack the RVs. Such a precursor attack would have to be carefully planned, because the precursor explosions would threaten the offensive objects as well as the defensive vehicles. In particular, the lightweight decoys would be especially vulnerable to such explosions, so the offense would have to be sure not to ease the task of discrimination for the defense. However, the sensing and guidance systems of the interceptors and kill vehicles are complex and intrinsically more vulnerable than the simple detonators carried by the RVs.

The Battle Manager is an ill-defined concept in current exo scenarios. Nevertheless, the exo system must include a component which collates all the incoming sensor data and co-ordinates the system's response. Naturally, the

Battle Manager could become a critical bottleneck for the system and a tempting target for the offense. To minimize the risk to the system, the Battle Manager function may be distributed among several large computers, separately located and perhaps mobile, any one of which could assume all of the Battle Manager tasks should the others be lost. Nevertheless, the preservation of the Battle Manager and its links with the rest of the system will be difficult under the stress of a determined attack.

2) Pin-down attacks. Based in underground silos, the probes and interceptors would be relatively safe from anything other than a direct hit by a nuclear weapon. However, if the system is to succeed in defending against a structured attack, it must be able to launch the probes and interceptors within a very short period. For the probes, this period might be as long as 20 minutes, from the time the Soviet ICBMs are launched until they re-enter the atmosphere. This may be shortened by the interval required for the early warning system to detect the ICBM launches and communicate a warning. For the interceptors, the launch period is much shorter. If the RVs are allowed to close within 1000 km of their targets, then the interceptors will have just enough time to ascend above the atmosphere before the RVs re-enter; there would be hardly any margin for delay. If the interceptors could be launched any time after the RVs had closed within 2000 km, then a window of approximately 2 minutes would be available for launch.

By exploding nuclear warheads near the launch sites of the probes and interceptors, the offense might be able to prevent their launch or destroy them after they are launched. The heavy debris excavated by a ground burst would remain aloft many seconds after the explosion, posing a hazard to an ascending interceptor. If weapons explode while the interceptor is ascending, it may be destroyed by nuclear effects. Although it might be difficult for the offense to place such warheads on target with ICBMs, due to the presence of the defense system itself, SLBMs might be able to penetrate below the defense system with very little warning.

3) Spoofing. Because timing is critical to the operation of exo BMD, the offense may attempt to disrupt the system's timing by spoofing the system's sensors. The goal of spoofing is to draw the defense into committing itself against a false threat so that it is unavailable to counter a later real threat. For example, the offense may launch a swarm of decoys rather than real RVs toward the US ICBM silos. Since the early warning system could not distinguish between decoys and RVs, the defense would be obliged to launch its probes to assess the threat. The offense would thus draw the defense without having to expend real warheads of its own. Naturally, the defense would retain reserve probes in anticipation of spoofing, but the offense could stage this tactic repeatedly. Providing enough probes to keep the system viable in the face of such tactics would sharply increase the complexity and cost of the system without adding to its value.

Spoofing becomes even more serious if the interceptors and not the probes perform the discrimination function. In this case the defense must launch its interceptors before discovering the attack is a hoax. Then the offense has a variety of options for overcoming the defense, as suggested by the following scenario. The offense could launch its attack in two waves, the first wave consisting almost entirely of decoys to imitate a massive attack. (An ICBM which might otherwise carry 10 real RVs could carry over 100 decoys instead.)

The defense might guess that this first wave was essentially a spoof, but would be obliged to assume that the offense had included at least one real RV per target. Without knowing how many real RVs the swarm contained, the defense must launch enough real interceptors to deal with the entire swarm. Only after the interceptors had reached altitude and uncovered their sensors could they discover that they had been spoofed. The second wave, consisting of many real RVs, would follow a minute or two behind the first wave, just out of range of the first wave of interceptors. Unless a fresh salvo of interceptors were available for launch, these real RVs would penetrate unimpeded to their targets. The defense might attempt to thwart this tactic by launching its ICBMs as soon as the attack was confirmed to be real (that is, as the few surviving RVs from the first wave exploded over their targets). However, coordinating these launches so that they occurred during the very short interval between the first and second attack waves would obviously be quite risky, especially with the uproar of the exploding first wave close at hand. The offense could make the problem even more awkward by exploding warheads from the second wave in the paths of the ascending missiles. Even with the most favorable outcome, the entire BMD system would have bought the defense a delay of about two minutes.

Such a scenario is by itself too simple to be taken very literally, but it could easily be made more complicated. The offense must gamble on the optimum number of RVs per target to send in the first wave. To conserve its assets, the defense must gamble on the offense's gamble. Perhaps the ICBMs could escape under fire between the two attack waves, or perhaps they would fail catastrophically. Both the offense and the defense must take enormous risks in these circumstances. The defense system may merely complicate these risks without actually reducing them. It is hardly the straightforward solution to ICBM vulnerability it may at first appear.

V. Performance Requirements

Since no definitive design of the exo system can be developed in the near future, it would be risky to speculate about the performance an exo system might actually achieve. On the other hand, it is possible to make some basic estimates of the performance the system would have to achieve in order to be attractive for specific strategic missions such as ICBM defense. Even very simple models can highlight important requirements for exo defense.

Soviet ICBMs carrying multiple independently targeted re-entry vehicles (MIRVs) pose the most obvious threat to the survivability of US ICBMs. Because ICBMs carry multiple warheads, a small number of Soviet ICBMs could in principle be launched to aim a large number of warheads at US ICBMs.

In fact, because the destruction of one US ICBM would eliminate several threatening warheads, the Soviets might be willing to aim several warheads at each ICBM silo. This places an enormous burden on a ballistic missile defense system. In order to preserve any one ICBM site from an attack by several RVs, the BMD system must destroy every (reliable) RV attacking it. Even if the probability of destroying an RV is relatively high, the probability of destroying all the RVs is significantly less. For example, assume that the BMD system can achieve a probability of 0.8 for destroying an RV; that is, the system can destroy 80% of the RVs it attempts to destroy. Such a success rate is exceptional for any military system, and is all the more remarkable given the special technical requirements of exo BMD. Yet if the Soviets aim eight (reliable) RVs at each target (a large but not unimaginable number), the probability for the survival of the target even if the defense attacks all eight is $(0.8)^8 = 0.17$, a potentially catastrophic dilution of performance.

This observation can be generalized. If the offense's sole objective is to destroy a specific target, it can in principle attack the target repeatedly in order to reduce the probability of the target's survival to any desired level, unless the defense is perfect. Only a small number of attacks is sufficient to reduce a high probability of successfully intercepting attackers to a low probability of surviving attacks. In fact, should they desire to destroy the US ICBM force, the Soviets already have enough RVs to attack each fixed missile site several times, and they can add many more RVs before a new defense system is deployed.

More complicated models of ballistic missile defense can be constructed to include many of the features already described for exo defense, such as preferential defense and decoys. While these add many parameters to the calculations, they do not fundamentally alter the observation that the defense will be at a serious disadvantage if the offense attacks each target with several warheads.

Such a model has already been discussed by Ashton Carter in his review of BMD for the OTA report on MX missile basing.[21] Carter's model did not include decoys but did include preferential defense and the support of a fairly effective endo defense system. An extension of the OTA model has been developed (see the Appendix) which explicitly incorporates preferential defense and includes decoys and discrimination. Results from the extended model confirm Carter's earlier conclusion that an exo system must achieve a very high level of performance to defeat a massive attack such as the Soviets could mount against the 1000 Minutemen silos by 1990.

The OTA model assumed that the Soviets would be able to aim 8 reliable RVs at each individual Minuteman silo, for a total of 8000 RVs. The USSR already has about 6000 RVs deployed on ICBMs, although of course at least some of these RVs would be reserved for targets other than ICBMs. Presented with the problem of overcoming a ballistic missile defense, the USSR might choose to enlarge this number considerably. It would therefore be imprudent to assume that the USSR would not be willing to aim 8000 RVs at US ICBMs. The additional deployment of 200 MX missiles at fixed sites would hardly alter this situation, except that the MX missiles might draw an even heavier attack because they each carry 10 RVs while the Minuteman III missiles carry 3.

The OTA model also assumed that the system would be supported by an endoatmospheric system (such as LoADS) which could intercept leakers. The assumed endo system could destroy the first leaker over each silo with a probability of 0.7, and could destroy a second leaker with a probability of 0.5. Three or more leakers would overwhelm the endo system and destroy the target.

These assumptions may be overly optimistic for the defense, in part because they place severe demands on the performance of the endo system. The original LoADS system was designed to defend each target only once. Possibly extra interceptors could be added if the burden of extra intercepts is not too great for the radar and the computer, and if the nuclear environment does not become too severe. Moreover, the mission of LoADS in an MPS role was different from the role it would play in supporting an exo system. While LoADS was required to achieve an intercept probability of only 0.5 or better in order to achieve an important strategic goal, an endo system in support of the exo system must achieve the best performance possible.

The exo system itself was characterized in the OTA model by the probability P_0 that the system would destroy a given RV. By varying this parameter, the OTA model showed that the success of an exo defense, even without the threat of decoys, depended critically on the system's performance as expressed by P_0.

The extended model described in the Appendix includes decoys. In the particular example presented here, it is assumed that the offense deploys five decoys with each real RV. Realistically, the defense cannot discriminate against these decoys absolutely; some decoys will attract KVs and some RVs will escape notice to leak through the exo system. Decoys and RVs are assumed to present to the defense two gaussian probability distributions whose means are separated by, for example, two standard deviations. This separation capability is sometimes expressed in BMD literature in terms of the K parameter. Roughly speaking, a value of $K = 2$ implies that the average difference which can be discerned between the measurements of RVs and decoys is about twice the typical error made in the measurements. The defense must then decide what fraction of the RVs, and implicitly what fraction of the decoys, it must designate for interception in order to achieve a successful defense. The defense may choose to defend a small number of targets vigorously. To accomplish this, a large fraction of the RVs must be destroyed, and therefore a large number of KVs must be wasted on decoys. Alternatively, the defense may choose to defend a larger number of silos less vigorously, so that (in the mean) the same number of silos survives. In this case, the defense will be somewhat more willing to tolerate leakers; consequently, a smaller fraction of the decoys aimed at defended targets will be destroyed. However, KVs will still be wasted defending silos which will ultimately be destroyed by leakers. The analysis in the Appendix shows that there is an optimum choice for defense strategy which minimizes the number of kill vehicles required to preserve a specified number of silos in the face of a specified attack. Typically in the present example, the defense must designate about 85% of the RVs for interception while wasting KVs on about 20% of the decoys. However, because there are five times as many decoys as RVs, more KVs are designated to attack decoys than to attack real RVs.

Each KV launched is assumed to destroy its designated target with a probability P_K of 0.9. Here again, the reliability assigned is open to debate. Among other things, reliability depends partly on readiness or availability. Individual missiles can be made to achieve an availability of 0.9 only with great difficulty in practice. However, in an actual engagement, the defense may be able to choose among several available KVs for each designated RV, so the issue of KV availability may not be a problem. Still, in performing a non-nuclear kill, the KV must achieve a remarkable technical feat with remarkable reliability. The defense may choose to designate two or more KVs per object to improve its effective reliability, but this of course multiplies the total number of KVs required.

The model also assumes that the defense exercises preferential defense, concentrating all of its resources to defend a specified fraction of the total number of silos. For the present example, the defense attempts to preserve 200 Minuteman silos out of the original 1000. In view of the realistic possibility of leakage, more than 200 silos must be defended to achieve this goal. If the defense can predict both the leakage rate and the number of KVs required to defend each silo, then the number of silos which must be defended as well as the total number of KVs required for defense can be calculated.

Some results from this particular example are shown in Table 2. Three different cases of discrimination capability (that is, values of the

Table 2 - Performance of BMD Layered System in the Presence of Exo Decoys

Exo kill probability: $P_K = 0.9$

Endo kill probabilities: $P_1 = 0.7$; $P_2 = 0.5$

(RVs/Target) N = 8

(Decoys/RV) D = 5

	x	P_R	P_S	R	T
K = 1.5	1.4	0.9193	0.5697	45.2	9040
	1.35	0.9115	0.5531	45.0	9000
	1.3	0.9032	0.5354	44.9	8980
	1.25	0.8944	0.5168	44.9	8980
	1.2	0.8849	0.4973	45.0	9000
	1.15	0.8749	0.4768	45.1	9020
K = 2.0	1.3	0.9032	0.5354	31.6	6320
	1.25	0.8944	0.5168	31.4	6280
	1.2	0.8849	0.4973	31.3	6260
	1.15	0.8749	0.4768	31.3	6260
	1.1	0.8643	0.4556	31.3	6260
	1.05	0.8531	0.4336	31.5	6300
	1.0	0.8414	0.4110	31.8	6360
K = 2.5	1.3	0.9032	0.5354	22.1	4420
	1.25	0.8944	0.5168	22.0	4400
	1.2	0.8849	0.4973	22.0	4400
	1.15	0.8749	0.4768	22.1	4420
	1.1	0.8643	0.4556	22.3	4460

discrimination parameter K) are shown. The variable x is in effect a measure of the vigor with which the targets are defended, and N_T is the number of kill vehicles required to preserve 200 Minuteman silos in the specified circumstances.

BMD performance is often characterized by cost-exchange ratios, but the present example illustrates that it is difficult to construct a specific definition for this concept. For example, consider an optimum defense when the discrimination parameter K = 2. For this case, the USSR has expended 8000 RVs (and 40,000 decoys) to destroy about 800 US ICBMs (corresponding to 2400 RVs if the US ICBMs happen to be Minuteman IIIs). The US has expended 6260 KVs while defending 420 ICBMs and preserving about 200. Even if the BMD system operates as expected, several thousand enemy warheads have been detonated over the US, along with several hundred smaller endo defense nuclear warheads. Among the many ratios which may be constructed from these numbers, which one accurately describes the utility of the BMD system?

While more detailed conclusions from the model are discussed in the Appendix, several observations stand out from this example:

1) When the offense aims many RVs at each individual target, the performance of the exo defense must be quite good in order to salvage a strategically significant fraction of the ICBM force. Unexpected small slippages in performance could have disastrous effects.

2) The exo defense requires a capable endo defense to support it in this example as in most realistic cases.

3) For optimal performance, the defense must decide how many silos to defend preferentially; this in turn requires a realistic prediction of system performance in advance.

4) The number of KVs required is most sensitive to the discrimination parameter K, which in view of the difficulties involved in infrared discrimination is the parameter most difficult to predict with confidence.

The caution should be added that these numbers are all only statistical averages obtained from a statistical model. If a BMD engagement is properly represented by one sample of a random process, the numbers arising from an actual engagement are likely to be different from those presented here, simply as a consequence of "luck", even within the limitations of the model. (In fact, the average deviations from these averages could be calculated from the model.) When all of the real complications of conducting a nuclear war are considered, the deviations to be anticipated become even larger. It is hard to imagine either side drawing any confidence from such analyses!

While they may not be numerically accurate, such examples illustrate that BMD in isolation solves the wrong problem. The real problem is that a relatively small number of fixed and identifiable targets (US ICBM sites) can be attacked by a large number of warheads (which could be carried by ICBMs or perhaps by other vehicles). If the number of targets (approximately 1000-1200 ICBM sites) can be multiplied by a significant factor (at least 4) - through deceptive basing, for example - then a realizable BMD might prove to be an effective additional deterrent. The obvious difficulty is that an expensive defense must be added to an expensive basing scheme for an expensive strategic weapon in order to restore (possibly) the survivability of ICBMs.

VI. Strategic Utility

The exoatmospheric missile defense system currently envisioned is applicable to a very specific scenario. It is assumed that at the beginning of a nuclear war, when all strategic systems are still intact, the Soviets would attack US ICBMs with their own ICBMs. A deployed BMD system might then insure that the US ICBM force could survive such an attack and remain available for retaliation. The analysis of the previous section makes it questionable whether a BMD system could in fact parry a determined Soviet attack on US ICBMs. Nevertheless, the BMD system must also be examined in the context of other possible scenarios.

Another role sometimes suggested for exo BMD is as a defense against submarine-launched ballistic missiles (SLBM). The exo system is not likely to be effective in this role. In contrast to ICBMs, which would be fired at long range from known launch sites, SLBMs could be launched over much shorter ranges from a variety of azimuths. The uncertainty of the launch azimuth further increases the amount of sky the BMD system must patrol. Worse, the SLBMs would follow lower trajectories for a shorter period of time, making them that much more difficult to track successfully.

Fortunately, contemporary submarine-launched missiles are not a threat to land-based hard targets because inevitable uncertainties in the position and velocity of the launch point make submarine-launched missiles relatively inaccurate. Nevertheless, the US is already proposing (for the Trident II D-5 program) to provide, through improved guidance, hard target kill capability for submarine-launched missiles by 1990. If they wanted to do so, the Soviets may be able to emulate this performance shortly thereafter.

It is sometimes suggested that advances in US anti-submarine warfare (ASW) capabilities may eventually confine Soviet submarines to protected home waters. While this outcome may be desirable, it is by no means a reliable projection at present.

It is appropriate to remember also that in addition to ballistic missiles there are other strategic systems such as bombers or cruise missiles for which exo BMD is totally irrelevant. In the absence of other defense systems effective against these threats, even a perfect area defense against ballistic missiles is virtually meaningless.

The BMD scenario implies that it would not be acceptable to launch US ICBMs under attack. In some cases, this presumption would be justified. Clearly, if an apparent attack by Soviet ICBMs on US ICBMs were the first indication of a nuclear war, it would be desirable to have an alternative to launching US ICBMs before the Soviet attack was absolutely confirmed. On the other hand, such a scenario is arguably unlikely, perhaps not worth such elaborate precautions. Almost certainly, a nuclear war would be preceded by unmistakably critical international tensions, such as a major war in Europe, perhaps involving the use of tactical nuclear weapons. Under such circumstances, a US President might find an attack by Soviet ICBMs sufficient grounds for launching US ICBMs also. Even if he were not willing to launch the ICBMs, and they were successfully destroyed by a surprise attack, US bombers and submarines would remain capable of effective retaliation.

The present Administration has placed public emphasis on the idea that nuclear war might be protracted over a period as long as six months. Rather than a direct frontal assault on US ICBMs, the BMD system may have to contend with a war of attrition in which critical system components were methodically reduced before US ICBMs were launched. For example, the Soviets could systematically attack US early warning satellites and US early warning radars, as well as the probe, interceptor, and Battle Manager sites of the BMD system. Such actions might make US ICBMs progressively more vulnerable without being sufficient to provoke their launch.

On the other hand, since they are relatively reliable for hard target kill, US ICBMs are likely to be expended relatively early in a nuclear exchange, thus leaving the BMD system nothing to defend.

Unquestionably, a defense of US ICBMs, if it were reliable, would make a significant contribution to deterrence. Nevertheless, it would not completely nullify Soviet ICBMs unless the Soviets chose to launch them futilely against an impenetrable defense. Instead, the Soviets might choose other more vulnerable US targets for their ICBMs. BMD therefore only partially avoids the destruction of nuclear war through deterrence; should deterrence fail, BMD may merely divert the destruction elsewhere.

The exo system currently envisioned would defend only ICBM sites. The defense of other targets must also be considered. Of particular importance is whether an exo system for ICBM defense could be expanded into an area defense system, especially in view of President Reagan's endorsement of defenses against ballistic missile attacks. Some view this possibility with satisfaction as the ultimate goal of BMD; others view it with alarm as a threat to arms control. In judging this issue, it is necessary to have a clear definition of what is meant by "area defense". In its simplest sense, area defense implies a system with sufficient range to protect large regions rather than single hard targets. Endoatmospheric systems such as LoADS lack the range for area defense, while exo systems necessarily have the range to satisfy this requirement. However, area defense further suggests that a system is sufficiently reliable to protect population centers from nuclear attack. This requirement is much more difficult to meet even if a system has adequate range.

If the Spartan missile is representative of future exo interceptors, one interceptor base could defend a region with a radius of several hundred square kilometers. By increasing the effective range of the interceptor, this defense coverage could in principle be increased (at some expense). However, as noted earlier, providing greater coverage forces the defense to commit its interceptors while the attacking RVs are at greater range. This as much as the performance of the interceptor itself will probably limit the coverage to be achieved from one interceptor site.

A single exo interceptor site defending an MX missile deployment, or two sites defending a large fraction of the Minuteman force, would therefore be able to cover only a small part of the continental US. To extend coverage to all the US would require perhaps a dozen additional interceptor sites, in a pattern comparable to the deployments proposed earlier for Sentinel or Safeguard. One could argue therefore that one or two exo interceptor sites would not and could not constitute a credible area defense. Although additional sites could be deployed for an area defense after the initial sites were installed, the new deployment would require several years (and considerable expense) to construct.

More importantly, the performance which can be realistically expected of an exo system falls far short of what would be needed for "area defense" in the larger sense. It is generally conceded even by BMD advocates[22] that because of the devastating consequences of only a few RV leakers, population defense is not feasible for the foreseeable future. Nothing in the proposed exo system justifies modifying that conclusion. On the contrary, in order to defend even hardened ICBM silos where leakage could be tolerated on a statistical basis, the exo system probably would require the support of an endo system which would be ineffectual for area or population defense.

For these reasons, it is highly questionable whether a small exo system deployed to defend ICBMs could be expanded into an area defense. Nevertheless, fears are often voiced that even a strictly limited point defense system will be perceived by the other side as an incipient "breakout" into an area defense. Precedents for such an extrapolation exist: US analysts have been fearful that the Soviet SA-5 high-altitude aircraft interceptor could be used in an ballistic missile defense role.[23] Perceptions often outdistance reality in the arms race. The US could find itself in the frustrating position of possessing an exo BMD system that others perceive as presenting an unintended threat which the system is unable to fulfill.

Opponents of BMD sometimes suggest that a BMD system could be used in support of a first strike. A nation possessing such a system might be tempted to believe that it could launch a pre-emptive attack on its opponent's nuclear forces, because the BMD system would further reduce the effectiveness of any retaliatory attack the opponent might be able to develop after absorbing a first strike. The BMD system could be brought to a much higher state of readiness in anticipation of this role than if it languished for years in expectation of an unlikely surprise attack. Rather than reducing the risk of nuclear war by deterring opponents, a BMD system would, according to this argument, make war more likely by making its possessor overconfident.

From a technical point of view, it is hard to endorse this idea. BMD systems are intended to defend fixed ICBM missile sites, but these missiles are precisely the ones most likely to be used as part of a first strike. After a first strike was launched, the BMD system would be left to defend mostly empty silos. More importantly, any nation launching a first strike must accept that a retaliatory attack could be directed against soft civilian targets instead of military targets. A BMD system deployed to defend missile silos would be poorly situated to cope with such retaliation. Any endoatmospheric defense would be totally out of range, and (for reasons already discussed) an exoatmospheric BMD system would not provide much protection even if the opponent's forces were seriously diminished. No informed national leader could realistically contemplate a first strike in the expectation that a BMD system would prevent decisive retaliation.

Whatever its utility, the most striking characteristic of this hypothetical exo defense system is its complexity. Successful operation requires the proper performance of many components, each of which will strain the state-of-the-art in its field. It is questionable whether such a system can ever be made convincingly reliable.

Proponents argue that other high-technology systems have already demonstrated the reliability of complex technology. Space programs are often cited in support of this claim. However, success in space operations often depends on conditions which are different from those faced by BMD. Space operations take place as the culmination of years of increasingly intense preparation, whereas BMD may be required to operate on short notice after years of dormancy. Space operations are routinely tolerant of significant delays when technical problems arise, while BMD would be required to perform instantly and completely on demand. Space operations typically take place over long periods of time. If problems arise, human engineers can often rearrange operations to salvage the mission. BMD operations would take place within an interval of less than half an hour, leaving no time for human intervention to overcome problems as they arise. Most importantly, space systems are not required to operate in the unprecedented environment of a nuclear war.

Exo BMD also differs from other high technology projects in its apparent lack of redundancy. The failure of any of the many key components of the system (such as early warning, tracking, discrimination, etc.) would lead to the collapse of the system as a whole. Nuclear power reactors (not now enjoying a reputation for reliability) offer an instructive contrast. The isolation of the reactor fuel from the environment is preserved by three separate components: the fuel cladding, the reactor vessel with its associated cooling system, and the containment structure, each of which is engineered as if it alone were the ultimate line of defense against nuclear release. The complexity of a nuclear power plant is in parallel, offering redundancy and therefore reliability, while the complexity of exo BMD is in series, with little opportunity for redundancy.

A consequence of this questionable reliability is that exo BMD threatens much more than it promises. Therefore, the deployment of a defense system with uncertain reliability and capability is a powerful spur to arms escalation. Whether or not exo BMD is reliable, the offense would feel obliged to take it seriously and to plan some expansion of its strategic capabilities in response. On the other hand, if exo BMD is not convincingly reliable, the defense would still feel obliged to expand its strategic capabilities to compensate for the system's deficiencies.

The exo BMD scenario may be taken as an instructive example of the well-known last move fallacy. It incorporates the implicit assumption that the offense can do little or nothing to overcome the defense system's innovations, so that the defense in effect has the last move in the competition. The last move fallacy has ironic precedents in the history of ABM and BMD. When the Sentinel and Safeguard systems were announced, critics pointed out specific technical vulnerabilities in the proposed systems. Population centers would be almost impossible to defend to the level required. The small number of powerful of powerful radars would be vulnerable to a concentrated attack. Decoys might distract the radars, or the radars might be blinded by thermonuclear fireballs from offensive warheads or even from the warheads carried by the defensive interceptors. At the time, ABM proponents conceded none of these issues, arguing implicitly that these problems were not significant. In other words, the defense would have the last move. Now, even BMD proponents freely accept that all of these difficulties would have rendered either Sentinel or Safeguard unworkable. The new exo system has been specifically structured to overcome these difficulties. Population defense has been abandoned in favor of hard target defense. Fixed radars have been replaced by lofted optical sensors. Infrared discrimination reduces the distraction of decoys, and non-nuclear kill avoids the effects of exoatmospheric fireballs. Still, the offense has several options for its next move after an exo deployment. Defending a small number of hard targets makes it possible for the offense simply to saturate the defense. The probes might be attacked at their bases or while aloft, discrimination could be foiled by lightweight but sophisticated decoys, and the offense might choose to detonate its own exoatmospheric explosions. While overcoming the problems of the last generation of defense systems, the new exo system fails to anticipate the problems of the next generation.

Nevertheless, the last move fallacy is an avoidable pitfall. There are in fact cases where strategic systems have preserved their intrinsic advantages. When it was perceived that surface facilities for launching missiles would be vulnerable to nuclear attack, ICBMs were based in hardened underground silos which would be invulnerable except for highly accurate attacks. It was anticipated that the accuracy required to destroy hardened silos would be unavailable for a considerable time, and in fact only recently has it been suggested that the security of the silos is questionable. Similarly, missiles were based aboard nuclear submarines in the expectation that locating submarines in the open ocean would remain difficult indefinitely, and there is still no evidence that submarine-based missiles will become vulnerable for the foreseeable future. These examples are meant to show that it is possible to predict future technical developments in strategic systems and to take advantage of these projections.

Inevitably, the question will be asked: "Would it work?" To this question there is a hierarchy of answers, corresponding to a hierarchy of ways in which the question can be more accurately phrased:

1) Can a non-nuclear kill vehicle intercept and destroy a ballistic re-entry vehicle?

2) Can an exo defense system intercept and destroy a large number of re-entry vehicles in a co-ordinated attack?

3) Can an exo defense system preserve a selected group of targets (such as ICBMs) against a particular kind of attack?

4) Can the defended targets be preserved against a variety of realistic attacks, so that ICBM survivability is restored?

5) Would a ballistic missile defense system contribute to a strategy of assured survival, advocated by some?

Although no definitive exo system design will be available soon, the evidence already presented suggests some answers to these questions:

1) The accuracy required for non-nuclear kill places far greater demands on interceptor guidance than the accuracy required for nuclear intercepts with the earlier Spartan system. The metaphor of hitting a bullet with a bullet appears to be far more apt in this case. While BMD officials express strong confidence that non-nuclear kill is feasible, doubts are understandable until realistic tests such as HOE (and the Air Force test of its ASAT vehicle) can be carried out to verify the predictions. At least this is one issue which can be settled by actual demonstration.

2) Of course, non-nuclear kill is only one function of a complex system which must successfully co-ordinate many functions to be able to detect, identify, track, and destroy large numbers of attacking RVs. The difficulty lies not so much in performing any one of these functions for any one attacking RV, although each of these functions presents its own formidable technical obstacles. (In particular, imaginative design of the offensive weapons, especially in the use of decoys, might make an adequate defense prohibitively expensive.) The challenge is to integrate all these functions so that the system as a whole is reliable in the face of the unprecedented circumstances of a large sophisticated nuclear attack. Whether this could be

accomplished at all is open to doubt; what is even more doubtful is whether the US could maintain confidence in such a system as a credible defense in such circumstances.

3) The scenario usually envisioned for an exo BMD system is the defense of ICBM silos in the event of a pre-emptive ICBM attack. If the number of targets (i.e., ICBM silos) is limited, the offense may find it feasible simply to overwhelm the defense. Although it may be possible to enhance the defense in order to offset an increase in the offensive threat, other options such as deceptive basing of the defended targets or negotiated limits on offensive weapons may prove to be more attractive means of maintaining a credible defense.

4) Even if an exo system could ward off a large pre-emptive attack by ICBMs, the defended targets would remain vulnerable to other kinds of attacks. The USSR may choose to develop accurate SLBMs which could destroy ICBM silos with little warning, in spite of the exo system which might be impotent against such attacks. An extended ICBM attack may suppress the early warning system or exhaust the supply of probes and interceptors, leaving the ICBM silos vulnerable. In the absence of continental air defense, the USSR could conceivably destroy ICBM silos with long-range bombers or even cruise missiles, although not without considerable delay and warning.

At best, therefore, a defense of ICBM silos could buy time, although perhaps not very much time. To avoid losing its ICBM capabilities, the US might be obliged to use them on short notice. Although many BMD proponents loudly deprecate a policy of launching ICBMs under attack (LUA) and advocate BMD as a means for avoiding LUA, in fact the ultimate source of credibility for exo BMD may be the threat of LUA if the defense system fails.

Finally, it should be obvious that BMD systems of the type considered here are totally irrelevant to a strategy of assured survival. The mission of an exo system would be to protect ICBM silos, some of which (unlike civilian targets) could be sacrificed selectively. Even then, a credible exo system would need the support of an endoatmospheric defense which, although it may be effective for hard target defense, would be unsuitable for defending soft targets such as cities. The exo system could defend only a fraction of the total area of the US surrounding the ICBM fields, and this region is unlikely to include large metropolitan centers. Curiously enough, the best that BMD could hope to achieve is the preservation of the US assured destruction capability.

VII. Conclusions

Some important conclusions can be drawn from this discussion of exoatmospheric ballistic missile defense:

1) Many of the components of the system are not available, and some will not be available for at least a decade. Of course, many of the component problems will undoubtably be solved, including perhaps some which currently appear to be insurmountable. However, when they will be solved, or whether they can all be solved, is unpredictable.

2) No integrated system has been designed, nor could any design be considered seriously until many of the component development problems are solved.

3) A very large BMD deployment, including both exo and endo systems, would be required to preserve even a small fraction of US ICBMs from a determined Soviet attack.

4) While the Soviets already have a large inventory of ICBMs, to which they can add, the US must build a BMD system from scratch.

5) The USSR is likely to adopt specific countermeasures against an exo defense. These could include pindown attacks (particularly by SLBMs) on probe and interceptor sites, nuclear precursors against probes and interceptors, or beam weapon attacks on the critical probes.

6) Reliance on passive infrared discrimination burdens the defense with serious technical problems while it allows the offense to develop simple, lightweight, but effective exo decoys.

7) An exoatmospheric battle is not likely to remain non-nuclear. The offense naturally would be willing to detonate nuclear precursors in support

of its nuclear attack, and in these circumstances the defense would have little reluctance to detonate large nuclear warheads within dense groups of RVs.

8) Because of its questionable reliability, an exo defense would probably be supported ultimately by a launch-under-attack (LUA) policy.

9) A BMD deployment would probably contribute to the arms spiral. Because the US could not be sure it would work, and because the Soviets could not be sure it would not work, each side would tend to expand its strategic forces even further.

10) Survivability of the ICBM force (or any other comparable set of fixed targets) will probably require a combination of three factors: (a) a proliferation of target points (through, for example, mobile or deceptive basing), (b) a limitation on strategic weapons, or (c) ballistic missile defense.

11) An exo system deployed to defend ICBMs could not easily be expanded into an area defense. Range limitations and the relatively easy penetrability of the system make it technically unsuited for such a purpose. General perceptions about a BMD deployment, in contrast with technical considerations, are an entirely different matter.

Notes

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22) See Note 4.

23) Mark M. Lowenthal, "The 1982 Review of the ABM Treaty," Congressional Research Service, The Library of Congress, Washington, D.C. (1982); Carnes Lord, "The ABM Question," Commentary, May 1980.

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Appendix

Computing the Performance of an Exo System Against Decoys

In his analysis of the BMD option for MX basing (for the OTA Report[1]), Ashton Carter alluded to a calculation of the performance of exoatmospheric BMD. He used this calculation to estimate the number of BMD interceptors required to preserve a minimum number of Minuteman silos from a hypothetical Soviet attack. Carter's calculation is reconstructed here, and is extended to include the effect of decoys.

Assume that the overall efficiency of the exo system is characterized by the probability P_o that a given re-entry vehicle (RV) will be destroyed before it re-enters the atmosphere. In the absence of decoys, this corresponds to the probability P_K that the defense can perform a successful intercept of an RV ($P_o = P_K$). Assume also that the exo system is supported by an independent endo system which defends individual point targets against RVs which "leak" through the exo system. The endo system can destroy one leaker with probability P_1, and it can also destroy a second leaker with probability P_2. Finally, assume that the Soviets target N RVs against each defended hard target.

The probability for survival of a defended target is then obtained through the binomial probability distribution. The probability that all N RVs are destroyed is simply P^N. The probability that one of the N RVs leaks through the exo system is $N \cdot P_o^{N-1} \cdot (1-P_o)$, but this leaker may be intercepted by the endo system with probability P_1. Similarly, the probability for two leakers is $1/2 \cdot N \cdot (N-1) \cdot P_o^{N-2} \cdot (1-P_o)^2$, but both leakers may be intercepted by the endo system with probability

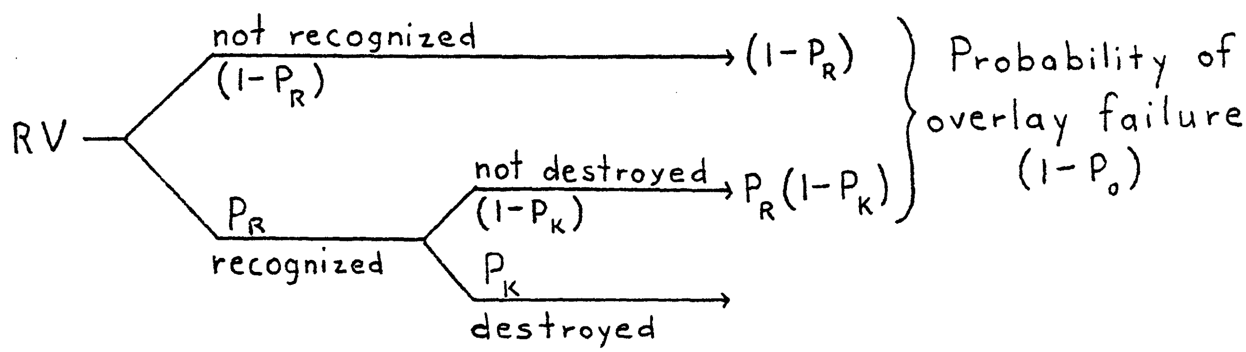
P_1P_2. In the event of three or more leakers, the defense will be overwhelmed and the target will be destroyed. (No adjustment is made for the intrinsic reliability of the RVs as this is probably quite high.) Therefore, the probability that the target survives is

$$P_S = P_0^N + NP_0^{N-1}(1-P_0)P_1 + \tfrac{1}{2}N(N-1)P_0^{N-2}(1-P_0)^2 P_1 P_2$$
$$= P_0^N\left(1 + \frac{N(1-P_0)}{P_0} P_1\left(1 + \frac{(N-1)(1-P_0)}{2P_0} P_2\right)\right)$$

(Carter's Formula).

Several simple observations can be drawn from this formula about system performance as a function of its parameters. First, as exo efficiency P_0 is reduced, the survival probability is reduced increasingly rapidly (whenever N is greater than one), as Carter showed in the OTA report. This non-linear behavior means that unless the system can reliably meet a minimum level of efficiency, there is a danger that the system could be overwhelmed in an actual engagement where P_0 was not quite as large as expected. Second, as the number N of attacking RVs increases, the system becomes more sensitive to the efficiency P_0. In an open-ended arms race between offense and defense, progressively more defense is required to offset an increment in offense. The cost-exchange ratio (however it is defined) is therefore a dynamic rather than a static quantity, becoming less favorable as the threat increases. Third, as either the number of attacking RVs increases or the overlay efficiency diminishes, the probability of survival P_S becomes increasingly dependent on the second and third terms in Carter's formula relative to the first term. Consequently, the performance of the defense as a whole becomes more dependent on the effective performance of the supporting endoatmospheric defense system. In contrast to a self-sufficient endo system such as LoADS in an MPS role, which could succeed in its mission of exacting a significant penalty from the attacker even if it met only a moderate threshold of performance, an endo system in support of the exo system must be made as efficient as possible.

The effect of decoys on system performance may be incorporated into the system efficiency, P_o. The exo system may fail with probability $(1-P_o)$ in either of two ways: the system may fail to recognize a true RV and allow it to leak through unchallenged, or the system may fail to destroy a recognized RV. Let the probability that the system recognizes an individual RV be P_R. The event tree for the exo system is then



The combined probability of failure is

$$(1-P_o) = (1-P_R) + P_R\,(1-P_K) = 1 - P_R\,P_K$$

so the overlay efficiency with decoys included is $P_o = P_R\,P_K$.

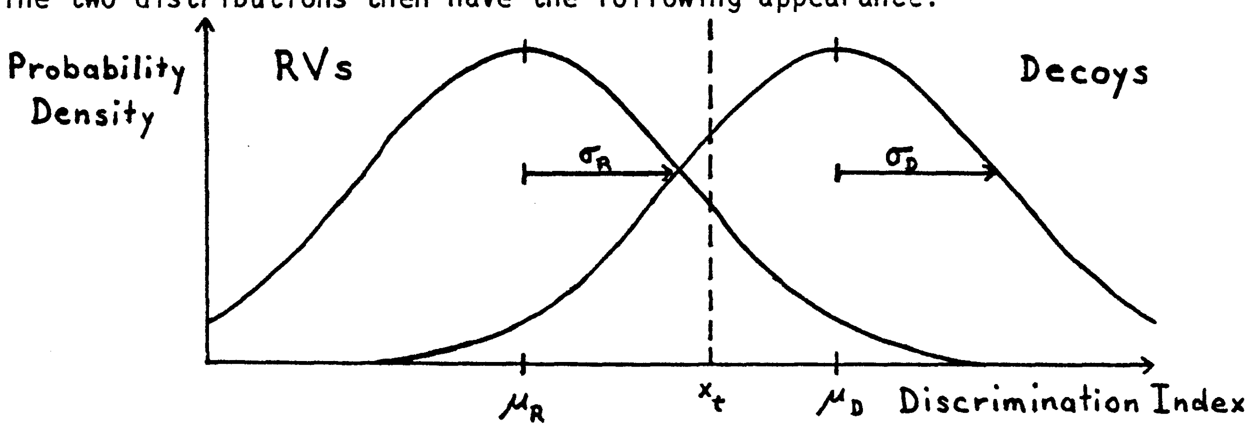
The exo system must allow some leakage because too many interceptors would be needed to attack all the decoys as well as all the real RVs. The defense must try to economize the number of KVs required to perform its mission, first by maximizing the discrimination between RVs and decoys, and second by tolerating the leakage of a calculated fraction of the RVs.

To perform discrimination between RVs and decoys, the system makes several measurements of the optical (and perhaps other) properties of the unknown objects. The various measurements can be combined, in principle at least, to produce one numerical index which characterizes an individual object. If this index exceeds a specified threshold, the system regards that object as an RV to be attacked; if the index is less than the threshold, the object is regarded as a decoy to be ignored.

Objectively, the indices for both RVs and decoys will be distributed randomly, each with a corresponding probability density function. It is common to assume that these two probability density functions will be gaussian. Almost certainly the index can be constructed so that the gaussian assumption is a good approximation; in the absence of real data it is at least an instructive example. The probability density for either RVs or decoys is given by

$$p_{R,D}(x) = \frac{1}{2\pi\,\sigma_{R,D}} \exp\left\{ -\frac{1}{2} \frac{(x-\mu_{R,D})^2}{\sigma^2_{R,D}} \right\} ,$$

where μ_R and μ_D are the means of the distributions for RVs and decoys, respectively, and σ_R and σ_D are the corresponding standard deviations. The two distributions then have the following appearance:



The system designer is free to pick a threshold x_t that arbitrarily determines which objects will be attacked as RVs . In the example shown, the system would attack the large fraction of the RV population to the left of the threshold. It would also attack the small fraction of the decoy population to the left of the threshold. While ignoring the large fraction of the decoys to the right of the threshold, the system allows a small fraction of the RVs to leak through.

Naturally, discrimination is more successful if the defense can further separate the two distributions by improving its observations of the attack. Conversely, the offense attempts to confuse the two distributions, most obviously by reducing the separation between the two means (that is, by making the decoys a better imitation of the RVs), but also by attempting to enlarge the standard deviations σ_R and σ_D (in effect, by making the nominal appearances of both RVs and decoys less specifically defined).

The parameter K is a measure of the separation of the two distributions which often appears in official discussions of exo BMD. When the two standard deviations are equal ($\sigma_R = \sigma_D$), it is defined as

$$K \equiv \left| \frac{\mu_D - \mu_R}{\sigma_{R,D}} \right| .$$

The figure has been drawn with a value of K = 2; that is, the means of the distributions are separated by 2 standard deviations.

It is immediately obvious that system performance will be sensitive to the selection of the threshold x_t, particularly when, as illustrated, the K parameter is about 2. Because few leakers can be tolerated, the threshold must be much greater than μ_R ($x_t \gg \mu_R$). In this region, the RV distribution is low so that only a few more RVs can be included if the threshold is increased further. However, because the decoy distribution in this region is large, a small change in the threshold represents a major change in the number of decoys mistaken for RVs. Therefore, in order to increase the overlay efficiency (P_0) slightly, the defense must expend many more KVs, most of which will be deployed against decoys (wastage).

The number N_K of KVs required per target defended is given by

$$N_K = N\left(P_R + D P_D\right),$$

where again N is the number of attacking RVs, P_R is the probability that an RV will be recognized and attacked, P_D is the probability that a decoy will be attacked, and D is the number of decoys accompanying each RV. Since the defense cannot be perfect, some defended targets will be lost to leakage. If the probability for survival of the target is P_S, then in order to preserve N_S targets (in the mean), the defense system (exo and endo together) must defend N_P targets, where N_P is given by

$$N_P = \frac{N_S}{P_S} \quad .$$

Consequently, a better measure of KV economy is the number of KVs required per <u>surviving</u> target:

$$R \equiv \frac{N}{P_S}\left(P_R + D P_D\right) .$$

Clearly, the total number of KVs required is then

$$T = N_S R \quad .$$

(The above equations are based on the assumption that only one KV is deployed against each object identified as an RV. If the kill probability P_K of each KV is low, the defense might choose to deploy more than one KV against some or all such objects. If the defense simply chooses to deploy two KVs against each object, then the number of KVs required is obviously doubled. In this situation, KV economy deteriorates so rapidly that an exo defense system may be unattractive anyway.)

The probabilities P_R and P_D are clearly the accumulations of their respective probability density distributions to the left of the threshold x_t. These are obtained in this example by integrating over the gaussian distribution as follows

$$\begin{aligned} P_{R,D}(x_t) &= \int_{-\infty}^{x_t} p_{R,D}(x)\,dx \\ &= \frac{1}{2}\left(1 + \operatorname{erf}\frac{x_t - \mu_{R,D}}{\sqrt{2}\,\sigma_{R,D}}\right). \end{aligned}$$

This result includes the well-known error function, the properties of which are summarized in Abramowitz and Stegun.[2]

If the arguments of the error function are defined as

$$a_{R,D} \equiv \frac{x_t - \mu_{R,D}}{\sqrt{2}\,\sigma_{R,D}}$$

then one can easily show that the two arguments are related by the equations

$$\begin{aligned} a_D &= \left(\frac{\sigma_R}{\sigma_D}\right) a_R - \frac{\mu_D - \mu_R}{\sqrt{2}\,\sigma_D} \\ &= a_R - \frac{K}{\sqrt{2}} \quad (\text{when } \sigma_R = \sigma_D), \end{aligned}$$

where again K is the discrimination parameter. Where necessary, these arguments can be obtained from their respective probabilities by inverting the error function:

$$a_{R,D} = \operatorname{erf}^{-1}(2\,P_{R,D} - 1).$$

The inverse of the error function is easily computed using the Newton-Raphson technique for finding roots.

When $\sigma_D = \sigma_R$, the problem may always be re-scaled without loss of generality so that $(\sigma_D = \sigma_R) \equiv 1$ and $\mu_R \equiv 0$. Then $K = \mu_D$, and

$$P_R = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{x}{\sqrt{2}}\right)\right)$$

$$P_D = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{x-K}{\sqrt{2}}\right)\right) = \frac{1}{2}\left(1 - \mathrm{erf}\left(\frac{K-x}{\sqrt{2}}\right)\right) .$$

(The reversal of sign in the last step is made to keep the argument of the error function positive and therefore within the domain of the applicable numerical algorithms.)

These results can be used to explore the sensitivity of the defense system to its operating parameters. It is necessary first to specify the following parameters:

a) the number of targets which must survive, N_S;

b) the number of RVs threatening each target, N, and the number of decoys accompanying each RV, D;

c) the performance of the supporting endo system, in terms of its kill probabilities P_1 and P_2;

d) the kill probability for an individual KV, P_K;

e) the ability of the system to discriminate between RVs and decoys, in terms of the parameter K.

Then the threshold x can be varied systematically. For each value of x, the following performance indicators can be calculated:

a) the probabilities P_R and P_D;

b) the probability of survival P_S, and from it and N_S the number N_D of targets to be defended (preferentially);

c) the number of KVs required R per target preserved, and from it and N_S, the total number of KVs required T.

If the defense wishes to minimize the number of KVs required, the value of x is chosen to minimize R. A larger value of x requires a larger number of KVs to defend a smaller number of targets more vigorously, while a smaller value of x again requires a larger number of KVs, this time to defend more targets less vigorously.

The model just described is meant only to be instructive, and should be regarded with caution. Simplifying assumptions have been made and many complications which might be included have been neglected. More importantly, the conclusions obtained from the model depend critically on the system parameters, and literally none of these can be specified definitely until the Soviet threat is better known and until a real defense system is designed. Nevertheless, the model can be used to set minimum requirements for a credible exo system.