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of Near-Term Strategic Defense*

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*Survivability and Effectiveness
of Near-Term Strategic Defense*

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CONTENTS

ABSTRACT	1
I. INTRODUCTION	1
II. COST EFFECTIVENESS OF ATTACK MISSILES	3
III. COST EFFECTIVENESS OF SPACE-BASED DEFENSE	4
IV. COST EFFECTIVENESS OF ANTISATELLITE MISSILES	7
V. THE EFFECTS OF HARDENING, MANEUVER, AND DECOYS	8
A. Carrier Vehicle Hardening	8
B. Carrier Vehicle Maneuver	9
C. Carrier Vehicle Hardening and Maneuver	9
D. Decoys	12
VI. GENERAL ARGUMENTS ON VULNERABILITY	14
A. Beam Weapons	15
B. Red-Out from Nuclear Explosions	15
C. Attrition During Peacetime	15
D. Vulnerability from Complexity	16
VII. CONCLUSIONS	16
FIGURES	19
REFERENCES	21

SURVIVABILITY AND EFFECTIVENESS OF NEAR-TERM STRATEGIC DEFENSE

by

Gregory H. Canavan and Edward Teller

ABSTRACT

This paper examines the survivability and effectiveness of space-based defensive missiles--a rapidly evolving technology--on a quantified basis. The effectiveness and costs of attack and defense are estimated and cost-exchange ratios are calculated in differing configurations. Various moves and countermoves are compared. Low-weight, self-reliant defensive missiles are found to be most effective. The advantages of the development of decoys for defensive missiles and of a small pilot deployment are discussed.

I. INTRODUCTION

Not surprisingly, political arguments and technical statements in the form of unproven assertions have clouded discussions of strategic defense. This paper is an attempt to place the discussion on a more scientific basis by comparing the effectiveness of attack, defense, countermeasures, and counter-countermeasures using various parameters. Throughout the paper, an attempt is made to state the essential assumptions on which comparisons are based. The principal purpose is to clarify rather than to convince.

The criterion proposed by Paul Nitze has found some agreement: it is worthwhile to deploy a defense if it is more cost effective at the margin (disregarding research and initial deployment expenses) than the countermeasures that could be used against it. This paper applies Nitze's criterion in a quantitative manner to nuclear attack missiles, to space-based defensive missiles that collide with missiles as they leave the atmosphere, to antisatellite missiles directed against space-based defenses, and, finally, to the costs of passive defensive countermeasures--hardening, evasive maneuver, and decoys--singly and in combination.

The purpose of the paper is to provide a coherent set of measurements that will help us answer questions as to (1) whether or not currently proposed space-based defenses would be effective and (2) what kind of defensive missiles would be most effective. The second question can be answered more definitively because changing the assumptions about the capabilities of such defense changes effectiveness more than comparative cost. Questions about the survivability of defense cannot be answered in absolute terms, but the conclusions indicate how survivability can be improved.

The Nitze criterion asserts the obvious truth that no military preparation is worthwhile if it can be countered at a lesser cost. Yet, the criterion may miscarry because of the fallacy of the last move--that is, the result may depend on the stage at which the chain of comparing moves and countermoves stops. The usual way to discuss the criterion is to propose space-based defensive missiles as a defensive measure and propose antisatellite missiles as a response to such a measure.

This report selects a special set of moves and countermoves. It first shows the obvious fact that nuclear-armed rockets are an economically effective, if horrible, method of aggression. It then discusses space-based defenses and the manner in which such defenses can be countered. The conclusion provides a discussion of the passive responses for frustrating antisatellite missiles. Because the last point is discussed both from the point of view

of the attacker and the defender, passive responses provide a natural stopping point in the chain.

Current plans call for carrier vehicles (carriers) with some number of nonnuclear, homing defensive missiles (defenders). That configuration and a newer design, a carrier with a single defender (singlet), are both assessed, as is the countermeasure of antisatellite missiles (antisatellites).

The Nitze criterion cannot be applied in a rigorous, quantitative manner when future technologies are involved. A cost comparison of 2:1 has little meaning; a cost comparison of 5:1 provides only an indication. On the other hand, comparisons of 20:1 can hardly be disregarded. Cost comparisons by themselves are not decisive; trends of cost comparisons are more important.

In evaluating the cost of a missile, estimates are uncertain for a number of reasons, including the difficulties of comparing U.S. expenditures to those of the Soviet Union. As a substitute, this paper bases comparisons of missiles and defenders on the masses to be lifted (payloads). They are also estimates, but the method of estimating them is less uncertain. Monetary costs are roughly proportional to the masses because launch costs are proportional to payloads. The cost of the colliding package depends on its mass, although construction costs also depend on the complexity of the package.

The main result of this discussion is that space-based defenders that are miniaturized, cheap, and self-reliant are preferable. That result is not surprising, but the detailed comparisons are illuminating and useful.

II. COST EFFECTIVENESS OF ATTACK MISSILES

The cost effectiveness of attack missiles can be estimated on the basis of current missile costs. A typical Soviet missile, for example, the SS-18, has about an 8-tonne payload mass, including 10 weapons weighing about 3 tonnes, fuel weighing 3 tonnes, and structural arrangements weighing 2 tonne.¹ The U.S. MX missile, of similar mass and payload, costs about \$200 million

in similar silo basing.² Assuming that the costs of the two missiles are similar, the current Soviet force of roughly 1,400 missiles has a total cost of about \$280 billion.

Estimating the cost effectiveness of nuclear-armed attack missiles is a logically necessary step. Thus, in a terrible sense, the cost effectiveness of that offensive measure, which could destroy a nation with an estimated monetary value of \$10,000 billion, can be generalized to a 36:1 ratio. (Although this is a large number, overestimates of the effects of nuclear explosions may have caused many readers to guess a higher figure.) Of course, the effectiveness of attack is undercut if defense is deployed.

A special point is that missile attacks using conventional high-explosive warheads would not be cost effective because their damage would be reduced by a factor of 10^3 to 10^6 . This point makes the connection between intercontinental missiles and nuclear weapons a quantitative proposition. Although the subject is not discussed here, the possibility of using chemical or biological weapons at shorter ranges should not be ruled out. The methods of analysis would be similar.

III. COST EFFECTIVENESS OF SPACE-BASED DEFENSE

The task of space-based defenders is to negate missiles by colliding with them. General analysis involves some complications, but the main issues can be discussed with simple models to the degree of accuracy required here.

Defenders and the sensors that support them must be predeployed at altitudes of 500 km or less to reach the attack missile before its weapons and decoys could be released. Current defender designs have a total mass of about 100 kg, 90% of which is propulsion. (Lighter defenders, which currently weigh about 30 kg, would reduce defender costs directly.) The carrier, which permits a number of space-based defenders to share common functions, could increase the total mass by 20% to 100%, depending on its size and design.^{3,4}

If a 100-kg defender hit and destroyed an SS-18-type missile before its warheads separated, 6 tons of useful payload would be destroyed for an expenditure of 100-200 kg. Depending on the weight of the carrier, such an action would result in a favorable mass-exchange ratio of about 60:1 or 30:1.⁵ A rough cost-exchange ratio can also be calculated because current defenders have an estimated total cost of about \$6 million each. Therefore, the cost-exchange ratio would be about \$200M:\$6M or 33:1. Thus, mass-exchange ratios may be reasonable substitutes for cost-exchange ratios. However, the Soviet missile costs used are obtained indirectly, and the space-based defender costs are based on designs, so both have significant uncertainties.

The exchange ratios must be adjusted to take into account both the effectiveness of the defenders and the number of defenders within striking distance of a particular launch. Defender effectiveness is high, so a 10% correction suffices. Absenteeism is a more difficult problem.

To reach a missile in boost phase, a defender must be within a distance equal to the product of its velocity and the time it takes the attack missile to accelerate and deploy its warheads. The acceleration-deployment time of SS-18 boosters is approximately 600 s. Thus, only about 20% of the defenders would be in a position to contribute to defense in a simultaneous missile launch, an absentee ratio of 5:1.⁶ (The remainder of defenders, of course, would be available to counter staggered or dispersed launches and submarine-launched missiles and for defense against reentering weapons.)

The attacker could increase the defender absentee ratio by replacing current missiles with missiles of shorter acceleration and deployment times (fast missiles), which would reduce the number of defenders that could reach attack missiles. For full effect, fast missiles should be launched from a more compact area. The size of the launch area could be reduced by deploying fixed silos close together or by moving mobile launchers to within a few hundred kilometers of each other shortly before launch.

Reducing launch time and radius by half during the next decade would increase the geometric absentee ratio to 20:1.⁷ If, however, the inclinations of the defenders were chosen to concentrate them over missile launch areas, the fraction of defenders available would double, reducing the overall absentee ratio to about 10:1.^{8,9} Predictions about absentee ratios are obviously uncertain because of the unknown properties of future missiles and their basing.

Fixed missiles should be relatively cheap but could be less survivable. Mobile missiles should be more survivable but could be more costly by a factor of 2 to 10 per weapon. Fixed missiles would support an offensive posture; mobile missiles could support either a survivable strategic withhold or a survivable defense that could penetrate defenses. Thus, advanced missiles would probably be faster but more expensive than current ones, so in the exchange ratio, one attribute tends to cancel the effect of the other.

Estimating on the basis of current defender costs and correcting for absenteeism, the cost-exchange ratio would be \$200M:\$30M (\$6M x 5), which is a little less than 7:1 in favor of the defense, and the exchange ratio in ten years (midterm) would drop to little more than 3:1. Although acceptable, both ratios could be improved by using smaller, cheaper defenders. The available technology is more capable of producing defenders that are lighter by a factor of 3 than are the designs assumed above, and continuing efforts on weight reduction and other innovations may further improve the exchange ratio. Reducing costs by a factor of 3 would increase the near and midterm exchange ratios in favor of defense by 20:1 and 10:1.

Overall, defenders appear more effective in the near and midterms, which counters the oft-repeated statement that defense may be offset simply by the deployment of more attack missiles. All of that, of course, depends on the next topic to be discussed--survivability.

IV. COST EFFECTIVENESS OF ANTISATELLITE MISSILES

Throughout the next ten years, the most effective countermeasure to space-based defenders is likely to be a guided missile armed with a nuclear weapon. Nonnuclear antisatellites would be lighter, but their decreased range of effectiveness would mandate an extensive increase in the accuracy and agility of antisatellites if defenders were equipped with sensors to detect them and propulsion and decoys to evade them. Therefore, this discussion assumes that the Soviets will rely on their existing strength in nuclear technology. Weapons of 10- to 100-kt yield would be used to minimize damage to the launch area. Such antisatellite weapons would weigh about 400 kg, divided more or less evenly between the warhead and the guidance system.

Antisatellites can use suborbital trajectories and thus need less final velocity than defenders, which must achieve orbit. If antisatellites could use a vertical-sounding trajectory, their weight could be reduced by a factor of 5 or 6. (However, these antisatellites would require a higher velocity to reach altitude and range before the carrier arrives and disperses its defenders.) The trajectory advantage of an antisatellite is about a factor of 2, making its effective mass about 200 kg.

Estimating the mass of a defender at 100 kg and that of the rest of the carrier at 100 kg (a total of 200 kg) gives an exchange ratio of 1:1. However, absenteeism reduces that ratio to 1:5 in the near term and 1:10 in the midterm. If the antisatellite could intercept a carrier containing 10 defenders, the exchange ratio would increase to 1:25 in the near term and 1:50 in the midterm. Current estimates of costs give an even more pronounced advantage to antisatellites under those conditions. A \$2 million antisatellite carrier attacking a current \$60 million carrier with 10 defenders would have cost-effective ratios of 30:1 in the near term and 60:1 in the midterm.

Those ratios are a strong argument for abandoning carrier vehicles with many defenders. The difficulties raised by antisatellites make the necessity for further measures clear.

V. THE EFFECTS OF HARDENING, MANEUVER, AND DECOYS

Passive measures for protecting defenders against antisatellites, such as hardening, maneuverability, and decoys, will engender obvious responses, so measures and countermeasures are discussed side by side. Although hardening, maneuver, and decoys used independently cannot ensure survivability, a combination of the three may succeed.

Cost effectiveness is assessed by comparing the masses required for hardening and maneuver with the mass of the antisatellite. Defense succeeds if the cost of the antisatellite is higher because the antisatellite could then be effectively negated.

A. Carrier Vehicle Hardening

A symmetrically exploding nuclear weapon of yield Y that attacks a defender hardened to withstand J fluence (radiation flux per unit area) has an effective range K equal to $(Y/4\pi J)^{1/2}$. Current satellites are protected against fluences of a few joules per square centimeter, so a 10-kt detonation at 10 km would destroy them. Hardening with a few grams per square centimeter of shielding allows a reentry vehicle to withstand the radiation flux of a megaton burst at 10 km (about 300 J/cm^2).¹⁰ Such an amount of radiation does not destroy the reentry vehicle but is assumed to crack the reentry heat shield. Defenders need not reenter, so the integrity of their shields is not essential, which easily ensures their survivability. Assuming that the amount of shielding needed is proportional to mass, one can estimate that about 1 kg/m^2 of shielding would be needed to protect a defender against a 10-kt attack at $K = 10 \text{ km}$. However, the calculations below use 10 kg/m^2 .

Early planning called for placing 1 to 10 defenders ($n = 1-10$) in a carrier so that they could share the overhead for communications, sensors, and other common requirements. Current plans emphasize singlets ($n = 1$), such as "brilliant pebbles." The area of a carrier increases as $n^{2/3}$, and the hardening mass per unit area scales as J , which is proportional to $1/K^2$. The total additional mass is proportional to $n^{2/3}/K^2$. Without

maneuverability, carriers on known orbits could be approached to within about 1 km by antisatellites. For $n = 10$ and $K = 10$ km, the penalty for hardening would be about 500 kg, which would not be acceptable. Moreover, because there is no limit to the accuracy of antisatellites, there is no limit on the hardening penalty either.

Thus, hardening by itself cannot ensure survival against antisatellites.

B. Carrier Vehicle Maneuver

To avoid interception by an antisatellite of effective range K , a carrier would have to maneuver a distance greater than K , about 10 km. The distance at which the carrier receives a warning and can then initiate its maneuver (range to maneuver or L) is crucial. If the carrier were warned when the anti-satellite was at a range of $L = 1,000$ km, the required deflection K/L would be approximately 1%. A carrier of mass M would have to expend fuel approximating $2M(K/L)$ in an evasive maneuver.¹¹

A carrier with 10 defenders of 100 kg each would weigh 1 ton, and other structures could increase the total to as much as 2 tons. In the latter case, the fuel for maneuver would be 40 kg, an exchange ratio for a mass of 400 kg to 40 kg, or 10:1 in favor of the carrier. After correcting for absenteeism (a factor of 5-10) and for antisatellite trajectories (a factor of 2), both in favor of the antisatellite, the exchange ratio is about even.

For protecting large carriers, maneuver alone achieves a draw, and even that result depends on the extent to which the antisatellite's maneuvers could offset those of the carrier.

C. Carrier Vehicle Hardening and Maneuver

Both the penalty for hardening ($n^{2/3}/K^2$) and the penalty for maneuver [$2M(K/L)$] favor carriers with fewer defenders per vehicle. Their sum is minimized by choosing an effective range K proportional to $(n^{2/3}L/M)^{1/3}$. Hardening and maneuver combined would then have a minimum penalty of additional mass that is proportional to $(n^{1/3}M/L)^{2/3}$. Scaling on the basis of number of defenders per carrier ($n^{2/9}$) and on the basis of mass $M^{2/3}$ (which

increases with n) indicates that a carrier with one small defender is advantageous. Scaling on the basis of the range to maneuver ($L^{-2/3}$) makes it clear that extending that range for the carrier through countermeasures, jamming, or signature cancellation is beneficial to defense.

Figure 1 illustrates the relationship between the amount of mass the hardened carrier would have to expend to protect itself at various ranges to maneuver and the number of defenders per carrier. Comparing the expendable mass of the carrier, rather than its total mass, with the total mass of the antisatellite (all of which is expended in the attack) is appropriate as long as the defense is successful. If the antisatellite succeeds, the carrier would be destroyed, and its total mass would also be expended. The calculations in Figs. 1 and 2 are made on the basis that the carrier survives.

The number of interceptors per carrier is shown along the bottom of Fig. 1, and the additional mass required is shown at the left. The solid lines in the figure ($L_{1,000}$, L_{300} , and L_{100}) represent, respectively, ranges to maneuver of 1,000 km, 300 km, and 100 km.

The lower dashed line indicates the estimated effective mass (20 kg) of an ideal antisatellite, and the upper dashed line indicates the effective mass (80 kg) of an antisatellite, whose effectiveness is degraded to 25% by countermeasures and by the strongly disturbed background produced by nuclear detonations.¹² The probable effective mass of an antisatellite is enclosed in the shaded region.

With the range to maneuver of 1,000 km, a singlet would need an additional 10 kg (3 kg for hardening and 7 kg for maneuverability, a proportion that holds for various parameters). The additional 10 kg would give a singlet a 2:1 advantage over an ideal antisatellite. That advantage persists up to carriers of 4 defenders.

Decreasing the range to maneuver to 300 km increases the additional mass required by a singlet to about 20 kg, which reduces the mass-exchange ratio to unity against ideal

antisatellites and to about 6:1 against real antisatellites. Reducing the range to 100 km puts singlets at a disadvantage against ideal antisatellites, although they still retain about a twofold advantage over real antisatellites.

The theoretical limit of the range to maneuver is set by the distance from the defender to the antisatellite launch area, but the practical limit is set by the ability of an antisatellite to detect a carrier and the ability of the carrier to counter antisatellite sensors. For the near term, antisatellites are unlikely to carry sophisticated on-board sensors. Instead, they would probably be assisted or guided by ground-based radars. If so, the antisatellite nuclear bursts would degrade or eliminate guidance early in the attack. Thus, the actual range to maneuver is determined by the interaction between limited antisatellite sensors and carrier countermeasures. That interaction depends on future developments and deployments, so the value of L cannot be specified. The best that can be done is to assess its impact parametrically.

The benefits of hardening and maneuver are marginal, particularly against improved antisatellites. Only the hardened, maneuverable carriers with a large warning range and a low mass lie within the region of probable, effective antisatellite masses shown in Fig. 1. Furthermore, the large exchange ratios favoring the antisatellite, discussed earlier, make it possible to use several antisatellites against one carrier. Such a scenario would make it necessary to increase the penalty for hardening and maneuver. However, carriers would become more survivable at all warning ranges if the mass of the defenders were reduced.

As seen in Fig. 1, optimal conditions are reached by singlets ($n = 1$). Figure 2 shows the exchange ratios for singlets with masses of 100, 35, and 10 kg, which can begin to maneuver at ranges L of 100 to 900 km, relative to an ideal 20-kg antisatellite. The first mass is typical of current designs; the second mass is typical of a brilliant pebble, based on the best of current technology; the third is a further step toward reduced

weight, which should be possible with technologies currently under development.

As shown in Fig. 2, the ratio of additional mass expended in maneuver by a 100-kg-hardened singlet with $L = 900$ km to the mass of an ideal antisatellite is approximately 3:1 in favor of the singlet. Against antisatellites that could reduce the range to maneuver to about 100 km, the exchange ratio would be about 1:1. With $L = 900$ km, a 35-kg singlet would have an exchange ratio of about 6:1, but that again would drop to unity if the anti-satellite reduced the range to 100 km. With $L = 900$, a 10-kg singlet would have an exchange ratio of 13:1; with a range to maneuver of 100 km, it would still have an exchange ratio of 3:1.

Thus, lightweight singlets appear survivable, provided the cost estimates are valid. However, costs can only be established with production runs of about 100 units. Although 10 to 100 times that number would be needed to provide significant boost-phase defense, deployment of 100 lightweight defenders could provide effective protection against accidental or third-country launches.

D. Decoys

The survivability of defense can be enhanced by increasing the number of objects antisatellites must attack. Used in combination with hardening and maneuver, they offer additional advantages. Hardening and maneuver reestablish the possibility that lightweight singlets may be cost effective. The next discussion shows that the use of decoys can establish a substantial advantage for defense.

The carrier could, on detecting the approach of an antisatellite, eject a number of decoys, which could drift to distances of a few times the accuracy range K of the anti-satellite in the approximately 100 s it would take for the antisatellite to arrive. Without sophisticated sensors, the antisatellite would have to pick an object and attack. For N decoys, the antisatellite would have a probability of about $1-1/N$ of surviving the attack.

However, if an antisatellite has some optical or infrared sensors, decoys would have to have the right shape and temperature. Decoys would also need some strength; otherwise, the antisatellite could use one burst to destroy the decoys and the second burst to attack the carrier. Therefore, credible decoys would probably need masses of about 1 kg.

For decoys to drift to a distance of a few K would require a velocity of about 0.3 km/s, a small movement that is difficult to observe. Suppressing decoys separated by distances of 2 K or more would require the attacker to commit an antisatellite to each object. Such a maneuver would require an additional 20 kg for each decoy.

Deploying decoys in a rough sphere would minimize the mass required. The carrier would have to be able to move to any part of the sphere to make all locations in the sphere credible. For N decoys, the radius of the sphere is $N^{1/3}K$, so the fuel for repositioning the carrier would have to be increased by $N^{1/3}$. If 30 decoys were used, the fuel needed to reposition the carrier would nearly triple.

Figure 3 shows the cost effectiveness of 0, 20, 40, 100, 200, and 400 decoys (1-kg mass) for 100-kg carriers with 1-9 defenders (100-kg mass) that have a range to maneuver of 1,000 km. The ordinate of the figure shows the ratio of the effective mass of ideal, 20-kg antisatellites needed to attack a carrier vehicle relative to the extra mass expended for decoys and to escape.¹³

A satellite without decoys is at a very strong disadvantage. Adding 20 decoys to a singlet increases its mass by 30 kg (20 kg of decoys and 16 kg of fuel and shielding). To counter, the attacker would need 21 antisatellites of effective mass, 20 kg each. If the attacker commits a weapon to each object around the carrier, the defenders should all be destroyed. The penalty on defense would then be 36 kg + 200 kg (the mass of the singlet) and the exchange ratio (420:236) at about 1.8:1.

For a singlet with 100 decoys, the extra mass totals 323 kg, and the overall ratio is 2,020:323, or about 6.3:1, which is a

significant improvement. For 200 decoys, the exchange ratio for a singlet is about 9.4:1. Decoys can also help carriers. A carrier with 9 defenders with 200 decoys would require 128 kg of additional fuel and shielding, a total of 1,328 kg (200 kg + 128 kg + 1,000 kg). The exchange ratio (20 x 201) to 1,328 is about 3:1, which is less than half of the exchange ratio for a singlet with 200 decoys. A singlet with 400 decoys has an exchange ratio of about 13:1. Thus, a combination of hardening, maneuverability, and decoys is three times more cost effective than hardening and maneuver alone.

The addition of each decoy requires the attacker to add a 20-kg weapon, which produces a limiting exchange ratio of 20:1 in favor of the defense. To reduce the exchange ratio, the attacker would have to discriminate the decoys in a short time at a great distance--a difficult task for which the defense can further respond. The contest would involve a technology where the free world has proven capabilities.

Active defense, or destroying the antisatellite, appears to be the only other currently envisioned countermeasure that could alter the situation in the time frame of interest. Such a defense turns out to be marginally useful, but by including that possibility in our discussion, we would need to further discuss the countermeasures available to the antisatellite.

As it stands, the effect of the passive measures available to the defense have been considered from the point of view of both defense and attack. So the discussion of moves and countermoves ends at this point. The successful performance of hardening, evasion, and decoys in combination appear to provide a significant advantage to defense. The Nitze criterion has been satisfied.

VI. GENERAL ARGUMENTS ON VULNERABILITY

A further number of countermeasures have been proposed to frustrate defense. Their nature makes it inappropriate to apply cost estimates at this time, so qualitative considerations must suffice.

A. Beam Weapons

At present, no nation has a beam weapon deployed in space, although the Soviets do have some ground-based beam weapons that could become effective. A long-range, rapid-fire, space-based beam weapon could be very effective against a space-based defender and particularly against carriers with several defenders. Even an expensive beam weapon could be cost effective in penetrating space-based defenses if it could protect a dozen or more attack missiles moving on roughly parallel paths.

The desirable countermeasures against such a beam weapon would be near invisibility and greater numbers of decoys. Each countermeasure becomes more feasible if small, independent, space-based defensive missiles are used. Using synthetic materials in construction would provide a smaller signature, and absorbing paint would help frustrate visual observation. In addition, small corner reflectors unfolded at some distance from the defender could serve as sensor decoys. Suppressing the visible and infrared emission from the jets propelling the defenders seems necessary and may be the hardest to achieve.

B. Red-Out from Nuclear Explosions

The detonation of a few hundred nuclear explosives in the high atmosphere would produce sufficient heat and radiation to make the launch of attack missiles and antisatellites difficult to observe. The condition, called red-out, would precede the attack, and the explosions would occur 2,000 to 3,000 miles from the launch sites, essentially on the high seas. (These explosions would be virtually harmless on the surface of the earth.) Such an attack strategy would not be significant because the nuclear explosions would give the defenders adequate warning to take evasive action. Concealing the plumes of the missiles in enhanced background would be more effective, although the strength of their signatures makes that unlikely.

C. Attrition During Peacetime

Another scenario would employ countermeasures against space-based defenders during peacetime. Although antisatellites would be effective in that role, their release might be viewed as an

attack, so the main danger in this case would probably come from ground-based lasers. Satellites might arguably disturb the aim or phase control of the laser beam, but such action against instruments in the attacking country could result in an even more serious form of hostile exchange.

The ideal response would be to deploy defenders so inexpensive that their replacement cost would be less than the cost of destroying them. That is the essential goal of deploying brilliant pebbles and is one of the reasons that space-based defenses have evolved from large carrier vehicles to singlets.

D. Vulnerability from Complexity

A complex design is vulnerable in each of its components and in every link between them. Space-based-defender designs that depend on sensor satellites and carrier vehicles, in addition to the defenders ejected from them, are much more vulnerable to failure. Because the success of the defense rests on the weakest link, the number of possible difficulties would remain disturbing even if each objection could be met.

The use of small, self-reliant defenders is the obvious answer. Progress toward miniaturization makes that possible.

VII. CONCLUSIONS

This study has two quite different conclusions, one probable and the other almost certain. Space-based defenses using miniaturization, sensors, computers, and decoys appear to have a reasonable chance to provide significant defense in the near future. This first conclusion is, of necessity, uncertain. Too many assumptions must be made to reach definitive, quantitative conclusions. Of particular importance is the cost of singlets.

The second conclusion is more certain. For survivability, defenders are best deployed in self-reliant singlets. In 1983, the singlet proposal would have evoked skepticism; today, the deployment of brilliant pebbles is clearly feasible. Practically every aspect of this study points to the conclusion that singlets are the best line of deployment. The Strategic Defense

Initiative Office has recognized the advantages and decided to develop singlets in competition with large carrier vehicles.

The cost-effectiveness studies in this paper lead to a practical recommendation about decoys. If the feasible countermeasure of an antisatellite missile is taken, decoys released in the last few minutes of the antisatellite's approach appear to be decisive to the success of defense. Therefore, considerable research and development effort should be given to decoys, particularly in finding a way to reduce the weight of a sufficiently imitative decoy.

The effectiveness of decoys could be improved by constructing singlets with superficial, but highly noticeable, differences so that the decoys need not imitate a single, well-defined signature. Singlet construction could also use modern composites, rather than metals, to minimize radar reflection.

This study also makes clear the difficulties of making decisions about defense, given the uncertainties about the costs of defense. Deployment of 100 singlets (without decoys) would permit more accurate information about the function and cost of a substantial system. It would also provide a good (though never complete) defense against missiles fired accidentally or by a terrorist state. (Unfortunately, the availability of missiles that could carry any of several highly effective tools of terror is steadily increasing.) Such deployment would mean that for the first time since rockets armed with nuclear warheads were deployed a quarter of a century ago, people within range of those terrible weapons would not be completely undefended against them.

The cost of deploying 100 brilliant pebbles is probably less than \$1 billion. Such deployment is an urgent and necessary step with several benefits. Political objections to a pilot development project could be overcome by making the enterprise an open, international undertaking. Such an undertaking would be particularly fitting because, since its inception, the Strategic Defense Initiative has intended to protect the whole of mankind--not just a single nation. A cooperative demonstration supported

in part by contributions from other nations would be a highly constructive step toward assured safety for all.

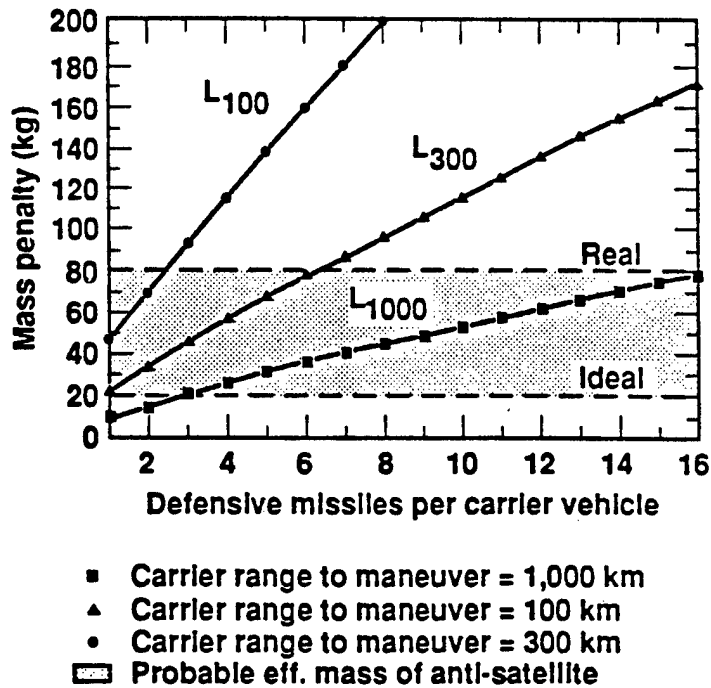


Fig. 1. Penalty for hardening and maneuver. Defensive missile = 100 kg, carrier overhead = 100 kg, ideal anti-satellite effective mass = 20 kg, and real antisatellite effective mass = 80 kg.

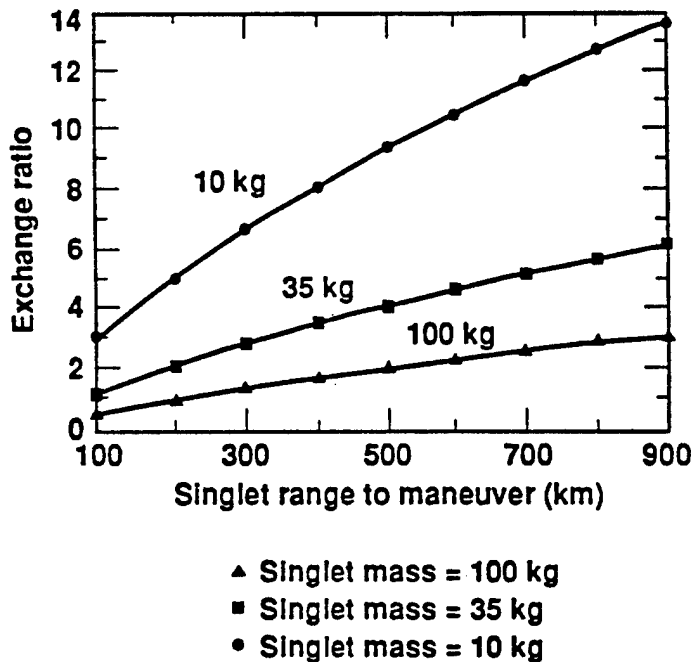


Fig. 2. The exchange ratio of singlet to ideal antisatellite. A singlet is one defensive missile and carrier and the antisatellite effective mass = 20 kg.

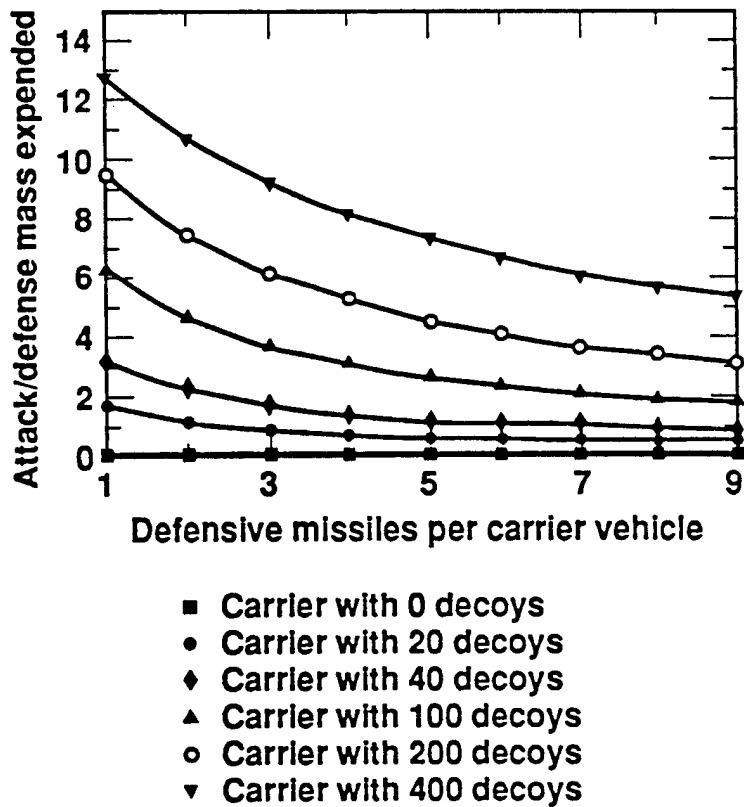


Fig. 3. The exchange ratio of defender and decoys to ideal antisatellite. Defensive missile = 100 kg, carrier overhead = 100 kg, decoy = 1 kg, range to maneuver $L = 1,000$ km, and antisatellite effective mass = 20 kg.

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1. N. Bloembergen and C. Patel, "Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons," *Reviews of Modern Physics* 59, 3 (1987).
2. U. S. Congress, Office of Technology Assessment, "MX Missile Basing," OTA-ISC-140 (U.S. Government Printing Office, Washington, D.C., September 1981). The total cost includes the initial purchase price plus life-cycle operating costs, which amount to about twice the initial purchase price, so the initial price could also be used for cost-exchange estimates. It is, however, conventional to base cost-exchange estimates on total costs, which is the approach used here.
3. J. Gardner, E. Gerry, R. Jastrow, W. Nierenberg, and F. Seitz, "Report of the Technical Panel on Missile Defense in the 1990s," Washington, D.C., Marshall Institute, 1987.
4. G. H. Canavan, "Defense Platform Size and Survivability," Los Alamos National Laboratory report LA-11244-MS (June 1988).
5. J. Gardner, E. Gerry, R. Jastrow, W. Nierenberg, and F. Seitz, "Report of the Technical Panel on Missile Defense in the 1990s," op. cit.
6. G. H. Canavan and A. Petschek, "Concentration of Defensive Satellite Constellations," Los Alamos National Laboratory document LA-UR-88-3510 (October 1988). If the effective radius of the missile's launch area is W , the missile's acceleration plus deployment time is T , and the defender's velocity is V , the defender can reach a missile within a range $R = W + V/T$ of the center of the launch area. Near-term values, $W = 1,800$ km, $T = 600$ s, and $V = 6$ km/s, give an R approximately equal to 5,400 km, which would enclose a geometrical fraction of about

$\pi R^2 / \pi 4 R_e^2$ or approximately 0.18 of the defensive constellation, where $R_e = 6,400$ km is the earth's radius. Concentrating the defender's inclinations over the launch area increases the fraction within range. In the near term, the concentration z equals about 1.1, which increases the fraction available to about 20%. Geometric estimates are within a 10-20% agreement with near-exact analytic solutions.

7. G. H. Canavan, "Directed Energy Architectures," Los Alamos National Laboratory report LA-11285-MS (March 1988); "SDI: the First Five Years," Proceedings of the Institute for Foreign Policy Analysis, Washington, D.C., March 13-16, 1988. If in the midterm the attacker decreased W and T by factors of 2 each, the geometric availability would drop by a factor of about 4. However, for those smaller launch areas, z would increase to about 2, so the absentee ratio would be about 10. Submarines could assemble before launch, but they could be addressed by absentees.

8. R. Garwin, "How Many Orbiting Lasers for Boost-Phase Intercept?" *Nature* 315, 286 (1985).

9. G. H. Canavan and A. Petschek, "Concentration of Defensive Satellite Constellations," op. cit.

10. R. Garwin and H. Bethe, "Anti-Ballistic-Missile Systems," *Scientific American*, 21 (March 1968).

11. To deflect a distance K over a range L (i.e., an angle $\delta V/V = K/L$), a defender of velocity V (about 7 km/s) with maneuver fuel of specific impulse c (about 3.5 km/s) must expend a mass $\delta M/M$ approximating $\delta V/c = (\delta V/V)(V/c)$, which is about $2K/L$.

12. The estimated effectiveness (25%) of an antisatellite armed with nuclear weapons in attacking a hardened, maneuverable defender may seem unduly low, particularly in comparison with the

high effectiveness (90%) originally estimated for defenders. Two reasons should be mentioned for that disparity. First, the booster leaves an extremely bright trail, which is easy to follow; the defender, on the other hand, can be made inconspicuous. Second, electronics technology has been applied with excellent results to guidance systems--a fact illustrated by the effectiveness of the Stinger missile used in Afganistan. Development of that technology in the western world far exceeds development elsewhere. Having said all that, however, both in this instance and in less conspicuous cases throughout the paper, our assumptions are necessarily uncertain.

13. The exchange ratios in Fig. 3 were calculated under the assumption that, if the attacker commits as many weapons as there are defensive objects, the carrier vehicle would be destroyed; therefore, the mass of the carrier has been added to the penalty of the defender. Thus, the exchange ratios shown in Fig. 3, which include the mass of the carrier, are lower than those in Figs. 1 and 2, which are based on the assumption that the carrier vehicle always survives.

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