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ASATs vs. Brilliant Pebbles

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ABSTRACT

This paper examines the cost exchange ratio of Brilliant Pebbles satellites when attacked by small, ground-based, non-nuclear ASATs. If the satellites have no defenses, the exchange ratio is likely to be at least 40:1 in favor of the attacker in a general war or 4:1 in his favor in a war of attrition. The use of maneuver, decoys, and space-based defensive rockets to defeat the ASAT threat were examined, but none of these approaches appears to be clearly economically advantageous.

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1 INTRODUCTION

One concept considered for a near-term ABM system is the deployment of small chemical rockets in space to intercept Soviet ICBMs in their boost phase of flight. These space-based interceptors (SBIs) could be augmented by a mid-course intercept system and possibly a terminal defense system.

The most promising candidate for an SBI system would appear to be the Brilliant Pebbles (BP) concept.[1] This concept is still in the development stage, but if it proves feasible and is adopted, one could expect that thousands of these small, "inexpensive" satellites would be deployed in relatively low orbits. Each BP satellite will consist of one lightweight SBI, a "cocoon" to house the SBI, shielding to protect against radiation from nuclear explosions, rockets and fuel to maneuver the satellite, solar panels to supply power, and a communications system. Reportedly,[2] the interceptor will weigh about 100 lb. Each interceptor will be completely autonomous after launch and hence will not rely on (possibly vulnerable) surveillance satellites for tracking of the ICBMs.

The Soviets can naturally be expected to try to negate any U.S. defense system. One countermeasure the Soviets have suggested is to attack the BP satellites with small, ground-based anti-satellite (ASAT) rockets using non-nuclear warheads.[3] These ASATs could be aimed at a satellite intercept point in space (either through inertial or command guidance), with the final trajectory corrections necessary for intercept being performed by on-board infrared (IR) sensors. The kinetic energy of the impact of the satellite and the homing vehicle would be sufficient to destroy the satellite.

The ASAT warhead could be relatively small. Over 5 years ago, the Air Force developed a miniature homing vehicle (MHV) for its aircraft-launched ASAT that weighed about 15 kg (33 lb), and development of MHVs that weigh a few kilograms or less is underway. For example, since the dry weight of the BP interceptor

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[1] Lowell Wood, Concerning Advanced Architectures for Strategic Defense, UCRL-98434, Lawrence Livermore National Laboratory, March 1988.
[2] "Strategic Defense System Space-Based Architecture Fact Paper," released by SDIO on Feb. 9, 1990, p. 3.
[3] "Gen. Surikov: How We'll Counter SDI," *Jane's Defense Weekly*, July 16, 1988, p.86.

will be under 10 lb, it is likely that the BP warhead will only weigh around 5 lb.[4]

To be economically and politically viable, any defense system must be designed to be cost-effective against an attempt to overcome the system. With that in mind, this paper will examine the cost exchange ratio of a Brilliant Pebbles space-based system when attacked by small, non-nuclear ASATs. Of course, the technical viability of both the BP satellites and the (less sophisticated) MHV-type ASATs is perhaps open to debate.[5] But for this paper, we will assume that both systems are feasible.

First, the general problem of ASATs vs. a space-based system is briefly discussed. Next, the cost of the BP satellite and the ASAT is estimated. Then the cost exchange ratio in a general war or a war of attrition when the BP satellites have no defenses is examined. Finally, the cost exchange ratio when the BP satellites are able to deploy various countermeasures is considered.

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[4]"Strategic Defense System Space-Based Architecture Fact Paper," p. 3. Also, General Dynamics is working on a kinetic kill vehicle with a projected mass of about 1 kg. Ross M. Jones, "Think Small -- In Large Numbers," *Aerospace America*, October 1989, p. 14.

[5]The BP system is still in the concept definition phase. The Air Force system was successful tested against an orbiting satellite, but, due to Congressional restrictions, it was never deployed. A new ground-based ASAT using a more advanced kinetic-kill warhead is now being developed by the Army. Deployment is planned for the mid-1990s.

2 ASATS VS. SPACE-BASED SYSTEMS

Before examining specific systems in detail, it is perhaps useful to consider the general problem of an ASAT attack on space-based defenses. Such an attack might take place as part of an attack on the U.S. or its allies, and thus as a prelude to war. In that case, the Soviets might try to "punch a hole" in the defense to allow its ICBMs to immediately escape. However, an attack on the space-based defense need not be part of a general attack. These weapons are orbiting over the Soviet Union with the explicit mission of disarming the Soviets. Thus, the Soviets could assert that it would be a legitimate defensive action to shoot the weapons down even in "peacetime". A war of attrition could result, with the Soviets shooting down satellites and the U.S. continually replacing them (if it were cost effective).

A small ASAT would appear to have a significant advantage over an SBI because the cost to put an object in orbit can be considerably more than to send it to the same altitude in direct ascent (see App. A). SBIs would probably be placed in polar orbits at an altitude of around 500 km. If an ideal space launcher is used to orbit the SBI, the direct-ascent rocket would have more than a 7 to 1 advantage.[6] If the ASAT warhead weighed less than the satellite being attacked, this would give an additional cost advantage to the attacker. For example, if the satellite weighed 100 lb and the ASAT warhead weighed 33 lb, the weight advantage would be 3 to 1 in favor of the attacker. In that case, a small, direct-ascent ASAT is likely to have at least a (3x7=) 21 to 1 launch cost advantage over an orbiting satellite.[7]

GENERAL WAR

If the attack were part of a general war (a one-time attack), there would be other significant cost advantages to the attacker:

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[6]In a war of attrition, the Soviets could launch a direct-ascent attack from wherever was convenient. For example, they might utilize the ABM radars around Moscow to support their attack. In a general war, the ASATs would intercept the relevant BP satellites just before the ICBMs were launched. This could require that the ASATs be launched from northern regions of the Soviet Union. Alternatively, the ASATs could fly "upstream" to intercept the satellites (rather than flying straight up). If they had to fly 1000 km upstream, the ASAT's advantage might be reduced to about 3.4 to 1 (see App. A).

[7]If the ASATs had to fly upstream, the advantage would be reduced to about 10 to 1.

1. *Satellite Availability.* All space-based systems start from a disadvantage because of geometry. Since at any one time, most of the SBIs will not be in range of the ICBM launch sites, only a small fraction of them will actually be able to participate in the engagement. The availability of the SBIs is quite sensitive to the time the booster burns and the time it takes the post-boost vehicle (PBV) to deploy the RVs.

If the ICBMs are attacked in the boost phase of flight (before RV deployment), probably only 1 or 2 percent of the BP interceptors would be available to participate in an attack against the Soviet ICBM force that is expected to exist in the mid-1990s[8] (see App. B). If those interceptors that can only reach the PBVs (rather than the boosters) are included, probably about 5 to 10 percent of the BP interceptors would be available.[9] On average, PBV intercepts will occur after several RVs (and perhaps numerous decoys) have been deployed, making them considerably less effective than booster intercepts.[10]

But just how effective would the defense have to be? That depends on what time frame one is considering. Paul D. Wolfowitz, Undersecretary of Defense for Policy, testifying before Congress on the goals of strategic defense, envisions "modest or moderate levels of defense, in the early stages of defense deployments, which could move us toward a new strategy of deterrence through direct denial as the defenses became increasingly robust."[11] It is reported that the initial (Phase 1) defense system must be designed to be effective against 50 percent of the Soviet SS-18 force and 30 percent of a first wave attack of 4700 warheads.[12] A more advanced

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[8]Against 1000 ICBMs, a boost-phase defense system with a 1 percent availability would require up to 100,000 BP interceptors, or 100 interceptors per ICBM. Since ICBMs probably cost $50 M-$100 M each, the BP satellites would probably have to cost under $1 M to be cost effective (for boost-phase intercept) against a proliferation of ICBMs.

[9]The small, cold PBV is much more difficult to detect, track, and attack than the booster, and a different set of sensors may be required for the task. To achieve this higher availability, it is assumed that the interceptor is launched when the ICBM launch is detected. The BP interceptor (while in flight) tracks the booster and then must acquire and track the PBV after it separates from the booster.

[10]If there were 10,000 interceptors attacking 1000 ICBMs, about 100-200 ICBMs would be caught in the boost phase and the rest would be attacked during some stage of the post-boost RV deployment.

[11]*Aviation Week & Space Technology*, June 26, 1989, p.31.

[12]Ibid., p.30

defense that supported a strategy of denial (in effect, a weapon-proof "shield" over America) would of course have to be much more effective than this.

2. *Multilayer Defense.* To achieve a high effectiveness, the ABM system relies on two or three layers of defense. However, the other layers of the defense depend critically on the success of the boost-phase intercept system to prevent the possible deployment of tens or hundreds of thousands of decoys. If the attacker can defeat the boost-phase intercept system, the other phases of the defense could probably be overwhelmed with targets, rendering the overall defense ineffective.[13]

As an example of the problems facing an ABM system in a general war, consider a system (with 10,000 SBIs) that cost about $20 B to deploy. If the availability of the system is 0.1, the Soviets would have to destroy 1000 SBIs (in a "hole-punch" attack) in order for 1000 ICBMs to escape.[14] If the Soviets were willing to spend as much as the U.S., they could afford to devote about $20 M to destroy each SBI. If the costs of the other layers of the U.S. defense are included, the Soviets might be able to spend $50 M or more to destroy each SBI.

A small non-nuclear ASAT could cost a few hundred thousand dollars (see Sec. 3). But even if it cost as much as $1 M, the Soviets could afford to send over 20 ASATs against each SBI.[15] If the satellite deployed no defenses and the probability of kill of the ASAT were high, this would represent a very large cost advantage to the Soviets (giving a cost exchange ratio of greater than 20 to 1 in their favor).

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[13]Richard DeLauer, when Under Secretary of Defense for Research and Engineering, noted that "any defensive system can be defeated with proliferation and decoys, decoys, decoys, decoys." (*Scientific American*, Vol. 251, no. 4, Oct. 1984, p. 47.) Of course, the other layers of the defense will have some capability to discriminate targets, but if this capability were sufficient in itself, there would be no need to deploy a boost-phase intercept system.

[14]Again, we are only considering the tactic of using ASATs to negate the defense. Other possible tactics might include proliferation of ICBMs and shortening the burn times of the booster and bus. For example, it is reported that the payload penalty for making a booster that will burn out in 100 s is quite small. "APS Study: Science and Technology of Directed Energy Weapons", *Rev. Mod. Phys.*, Vol. 59, No. 3, Part II, July 1987, p. S30.

[15]If (in contrast to the BP concept) there were N SBIs on each satellite, the Soviets could afford over 20xN ASATs per satellite.

Defenses If there were defenses (such as decoys) for the BP satellites, this would obviously complicate the assessment. The cost exchange ratio would depend on the effectiveness of the defenses and their cost relative to the cost to overcome them. For example, in the above case, if the defense of each satellite could be overcome by 20 to 50 ASATs, the exchange ratio would favor the Soviets even if the countermeasures taken to defend the satellite were free. If it took more ASATs, a detailed calculation would have to be made (see Sec. 5).

WAR OF ATTRITION

In a war of attrition, the Soviets would not have the large leverage of low satellite availability. Nevertheless, as noted above, the launch-cost advantage of a direct-ascent ASAT could make a war of attrition cost effective against a space-based defense. If that were the case, there could be a number of reasons that the Soviets might prefer an attrition strategy over a general war. For example:

-- The Soviets might not want to start World War III, but might desire to eliminate the perceived disarming threat represented by a space-based defense, and

-- Some countermeasures that the U.S. could possibly deploy might be easier to deal with in a war of attrition.

Of course, attacking U.S. BP satellites in peacetime would appear to be a very serious move fraught with many possible dangers. On the other hand, the Soviets have stated that they would consider the placing thousands of BP satellites overhead to be part of a first-strike strategy designed to disarm them.[16] Even the "modest" Phase 1 deployment of about 4500 BP satellites could be seen to be very effective in handling the residual survivors of a U.S. first strike[17] and thus to be a severe threat to their national security.

In practice, if the Soviets attacked the BP satellites, there might be few effective responses for the U.S. Of course, if the U.S. had a "perfect" defense, it could threaten to attack the Soviet Union

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[16]*Jane's Defense Weekly*, July 16, 1988, p.86.

[17]Cf. George Smith, "Brilliant Pebbles" Utility After an RV Attack on Soviet ICBM Silos, Lawrence Livermore National Laboratory, Feb. 7,1990.

if it started a war of attrition. However, a completely effective defense against an *alerted* Soviet Union is unlikely,[18] and thus any threats of preemptive nuclear war would be hollow. And indeed if it appeared that a perfect defense *were* feasible, it would offer a very strong incentive for the Soviets to attack the space-based system well before it reached that stage of development. In fact, it could be argued that the most "logical" strategy for the Soviets would be to shoot down each BP satellite immediately after it is put into orbit.

Alternatively, the U.S. might retaliate by shooting down some Soviet space-based assets (satellites). But then the Soviets would begin shooting down our assets. Eventually, we could end up destroying all the space-based assets on both sides. However, it is not clear that this would be to our advantage since we are probably more dependent on space than the Soviets. But even if it somehow favored the U.S., the threat of a space war still might not deter the Soviets if they thought the alternative for them would be unilateral disarmament.

Thus, it would appear that neither a general war nor a war of attrition should be ruled out by the space-based system's designers, and both will be considered in this paper.

[18]The effectiveness of a *surprise* attack is perhaps another matter.

3 COSTS

3.1 ORBIT COSTS

If a space-based defense is to be deployed in this century, the choices for a launch vehicle are probably limited to the Space Shuttle or an expendable launcher similar to the Titan IV.

The Space Shuttle was designed to lift about 60,000 lb into a 60° orbit to an altitude of about 300 km. However, most studies indicate that SBIs would be placed in polar orbits at about a 500-km altitude. In that case, the shuttle could only lift about 25,000 lb.[19] According to the GAO,[20] the launch cost of the shuttle in 1983 was about $266 M. If we assume a future launch cost of $200 M for the shuttle, the cost to lift a satellite to the appropriate orbit will be about $8,000/lb. Thus, the launch cost for a 100-lb BP satellite should be about $0.8 M

The Titan IV reportedly costs about $220 M and has a launch capacity of 39,000 lbs in low earth orbit[21] (LEO). A planned upgraded version of the Titan IV could possibly deliver about 48,000 lb to LEO and 30,000 lb to an 80° orbit at a 500-km altitude.[22] If this upgrade Titan IV cost about $200 M,[23] the satellite launch cost will be about $6700/lb.

One might expect future launch costs to be lower. However, past forecasts of extremely low satellite launch costs have failed to materialize, and some argue that they are unlikely to succeed -- at least with the use of rockets. For example, according to George Keyworth, former Presidential Science Advisor, and Bruce Abell: "The fundamental barrier to reducing the costs of space launch with rockets is technical -- the need to carry on board both fuel and

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19 In practice, the shuttle might be able to put less than 20,000 lbs into this orbit. *Aviation Week & Space Technology*, Jan. 26, 1987, p. 24.

20 Issues Concerning the Future Operation of the Space Transportation System (Washington, D.C.: GAO, Dec. 28,1982).

21 *U.S.A. Today*, June 15, 1989.

22 The large payload is obtained by using an elliptical (rather than circular) orbit for the Titan IV to insert the BP satellites into orbit. The small BP satellite rockets would be used to circularize the orbit of each BP satellite.

23 Martin Marietta estimates the cost of the upgraded Titan IV (including payload integration costs) to be about $100 M (assuming 28 launches per year). This implies (based on reported Titan IV costs) that the government launch costs are about $100 M.

oxygen. That imposes an inescapable weighty burden on rockets of any kind and a minimum cost of at least $5000 per pound to put something in space."[24]

Nevertheless, several Advanced Launch Systems (ALS) have been proposed. For example, the Martin Marrieta Corp. suggests that a system could be built to deliver 100,000 lb in LEO and about 66,000 lb to a BP satellite orbit.[25] The goal would be to have the launcher and payload integration cost no more than about $50 M. Government launch costs are difficult to estimate, but it is possible that they could drive the total launch cost up to $100 M, if not more. In that case, the satellite launch cost would be about $1500/lb. The target launch cost of other proposed ALS boosters is likely to be similar.

Originally the deployment date of this new generation of boosters was suggested to be around the year 2000. However, it now appears that, due to budget constraints, it could be considerably later before they could be available.[26]

Table 1 summarizes the satellite launch costs for various launchers. In the near term, the launch cost is likely to be at least $6700/lb. The BP interceptor reportedly will weigh 100 lbs. The cocoon, fuel for maneuvering the satellite, power, and the communications system will obviously increase the total weight. However, we will assume that the entire BP satellite will weigh only 100 lb. In that case, the launch cost could be about $670,000 per satellite. If future economies in launch costs are realized (by no means a certainty), the cost could drop to around $150,000 per satellite (or even less, if one is truly an optimist).

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[24]G. A. Keyworth II and Bruce Abell, "The Third Generation of the Space Age," *Science*, Vol. 245, p.16, July 7, 1989. The authors argue for the development of the National Aerospace Plane (NASP) which they believe would significantly lower launch costs for small satellites. However, because of its small payload capacity, the NASP would probably be an impractical means of delivering BP satellites.

[25]Again, using an elliptical "insertion" orbit.

[26]"The Air Force's Space Systems Division has been directed to terminate design work on the Advanced Launch System (ALS) program...The Air Force directive received Dec. 8 would disband the ALS joint program office to focus on technology research rather than system development...The budget cutting move, at best, would delay introduction of the advanced boosters and result in the continued use of present U.S. launch vehicles and their derivatives well into the next century." *Aviation Week & Space Technology*, Dec. 18, 1989, p. 112.

TABLE 1 SATELLITE LAUNCH COSTS

LAUNCHER	SPACE SHUTTLE	TITAN IV (U)	ALS
LAUNCH COST	$200 M	$200 M	$100 M
PAYLOAD (LB) 60°, 300 KM	60,000	48,000	100,000
PAYLOAD (LB) POLAR, 500 KM	25,000	30,000	66,000
COST/LB POLAR, 500 KM	$8000	$6700	$1500

3.2 BP SATELLITE COST

As noted, the BP satellite consists of a number of components and will incorporate the latest advances in technology. Of course, at this stage, it is difficult to accurately estimate the actual eventual cost of a BP satellite since one has not been built. Lowell Wood, the inventor of the BP concept, recently stated at an official Department of Defense briefing that the estimated "unit fly away" cost of a BP satellite would be about $1.1 M to $1.4 M.[27] Assuming that this proves to be correct, the total cost (including launch costs) of an on-station BP satellite would probably be about $1.8 M to $2.1 M for satellites launched in the next decade or so.

3.3 ASAT COST

The ASAT consists of a rocket and its payload (homing vehicle and fuel). The ASAT rocket could be of a fairly simple and efficient design. All it has to do is deliver the homing vehicle to a 500-km altitude at a time and place of the Soviets' choosing. Appendix A (based on simple, non-optimum designs) indicates that a two-stage ASAT rocket designed to reach an altitude of 550 km (for some flexibility) will weigh about 7 times its payload weight. If, for

[27]Department of Defense Special Briefing on the Strategic Defense Initiative, February 9, 1990. Also see *Aviation Week & Space Technology*, Feb. 26, 1990, p. 62. The total cost of the Phase 1 defense system was put at $55.3 B. This includes $13 B for space-based surveillance and tracking systems, $12 B for 4614 BPs, and $5.3 B for launch costs.

example, the ASAT payload weighed about 33 lb (15 kg), then the rocket would weigh only about 230 lb.[28]

Small rockets are relatively inexpensive, and the Soviets have had considerable experience in this area, having produced over 140,000 surface-to-air missiles in the decade from 1977-1986.[29] Table 2 lists three U.S. air defense missiles, and indicates that a 230 lb ASAT missile (excluding the guidance system and the payload) would probably cost less than $15,000.[30] Thus, missile (and hence payload) size is clearly not a critical factor. For flexibility, we will choose an 800-lb rocket, about 3.5 times the required size. This would allow the Soviets to provide some combination of increased range and payload -- perhaps to fly "upstream" rather than straight up; include added fuel to maneuver the homing device; or include an explosive (or even a small nuclear) warhead. The cost of a rocket this size (again, excluding guidance and payload) would probably be about $50,000.[31]

TABLE 2 MISSILE COSTS

AIR DEFENSE MISSILE	WEIGHT	COST	COST PER LB
CHAPARRAL	190	$12,000*	$63
IMPROVED HAWK	1400	$155,000*	$111
PATRIOT	2200	$120,000**	$55

Source: *DMS Reports* (1988)
*With warhead
**Excluding guidance and warhead

The cost of the ASAT payload is uncertain. The cost used here for the BP satellite (including warhead, rocket, communications, power, and housing) was $1.1 M to $1.4 M. How much of this is attributable to the warhead is unclear. At any rate, the BP warhead

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[28] A comparable-sized Soviet missile is the SA-8B mobile air defense missile which weighs about 420 lb. Six SA-8B re-loadable missile launchers are carried on a small truck.

[29] Soviet Military Power,1987 (Washington,D.C.: GPO, 1987).

[30] Assuming that the missile costs about $63/lb.

[31] Even cheaper methods of launch could be possible. For example, it might be more economical to load a large number of ASAT warheads on one larger missile (depending on how far apart the BP satellites were and how much extra fuel would be required to maneuver the ASAT warheads into position). Also, if the weight of each ASAT warhead were reduced to a few kilograms, it might be feasible to use rail-guns or gas-guns to launch them instead of rockets.

is almost certainly more complicated than what would be required for the ASAT. For example, the ASAT warhead could be a homing vehicle similar to the one used on the Air Force MHV system.[32] It could either be inertially guided or command guided by a ground-based radar to a nominal intercept point in space. The final "end-game" would be conducted by on-board systems which would consist of a small infrared sensor to detect the BP satellite and a computer that would command maneuvers to home on the satellite. The MHV would either physically hit the satellite or deploy a fragmentation warhead when it got close enough. The BP satellite would be destroyed by the hypervelocity impact of the fragments.

One knowledgeable analyst in this field estimates that a typical cost of such a warhead would be about $100,000.[33] If we assume that the rocket guidance system also costs about $100,000, the total cost of the ASAT rocket and warhead system would be about $250,000. However, recognizing the general uncertainties in this area, we will double this estimate and use $500,000.

Of course, since we are dealing with new, sophisticated systems, estimates of the cost of the BP satellite or the ASAT homing vehicle could easily prove to be overly optimistic. However, if costs escalate, it seems likely that the ASAT warhead will remain less expensive than the BP satellite since the innovative technology and level of complexity required of the BP satellite appear to be significantly greater than that required for the ASAT MHV (which essentially relies on well established technologies). Thus, none of the basic conclusions that follow would likely change.

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[32]The Department of Defense reports that the Soviets have for some time had research underway on kinetic energy weapons and that current Soviet guidance and control systems are probably adequate for effective kinetic energy weapons used against satellites. Soviet Military Power,1987 (Washington, D.C.: GPO, 1987), p.51.

[33]Gregory H. Canavan, An Assessment of Strategic Defense, LA-UR-87-520, Los Alamos National Laboratory, 1987, p.57, footnote 62.

4 COST EXCHANGE RATIO WITHOUT SATELLITE DEFENSES

4.1 COST COMPARISONS

Beyond the general uncertainties in the cost of future systems, there are many other difficulties in accurately comparing the costs of the defense and offense. At the most fundamental level, there is the methodological problem of evaluating Soviet military efforts in dollar prices. In reality, the price structure of a centralized planned economy often bares little resemblance to market prices. In this paper, we are forced to the expedient of evaluating Soviet costs in terms of "similar" U.S. systems.

It is also important to decide just what costs are to be included in the offense and the defense. For example, the cost derived in the last section for the ASAT is essentially the marginal cost to add a new ASAT to the system. Presumably, the "fly-away cost" given for the BP satellite is the same thing.

Other additional costs one might consider are operation and maintenance (O&M) costs over the lifetime of the system -- apparently about 10 years for the BP satellites. For example, the BP system would have to maintain a command, control, and communications network and occasionally replace (after perhaps retrieving and repairing) failed satellites. The ASAT O&M cost could probably be kept to a minimum since the ASATs could be based on present military bases or on ships which are already equipped to handle missiles. Most of the ASATs could be kept in storage until they were needed (since the Soviets would have the initiative). Without specific details of the systems, it would be difficult to estimate these costs.

Another approach would be to include the cost of the entire U.S. defense system since negating the space-based defense would probably nullify the effectiveness of the entire system (see Sec. 2). Thus, if the total defense cost $55 B and there were 4600 BPs, one could allocate a cost of about $12 M to each BP (or perhaps considerably more if O&M costs were included). Of course, the cost of the ASATs would also go up if overall system costs were used (although perhaps not significantly since the ASAT could for the most part use in-place facilities and sensors already built for other purposes).

Canavan and Teller in a recent paper on the effectiveness of strategic defenses suggest that the Nitze criterion should be used when comparing costs: "It is worthwhile to deploy a defense if it is more cost-effective at the margin (disregarding research and initial deployment expense) than the countermeasures that could be used against it."[34] Following this suggestion, we will use a nominal cost of \$2 M for the BP satellite (including launch costs) and a nominal cost of \$0.5 M[35] for the ASAT.

4.2 GENERAL ATTACK

Consider the case where the Soviets try to punch a hole in the defense in order to allow their ICBMs to escape. The cost exchange ratio (ER) can be defined as

$$ER = \frac{\text{COST TO U.S.}}{\text{COST TO USSR}} .$$

For a space-based system (without defenses), this becomes[36]

$$ER = \frac{S}{\beta A}$$

where

S = the cost of a BP satellite (including launch costs)

β = availability of BP satellites, and

A = cost of a Soviet ASAT.

In order for the exchange ratio to be in favor of the U.S., we must have

$$S < \beta A .$$

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[34]Gregory Canavan and Edward Teller, "Survivability and Effectiveness of Near-Term Strategic Defense." To be published in *Nature*, April 1990.

[35]The extra \$250,000 over the original cost estimate could be considered as the O&M costs of the ASAT.

[36]Assuming (for simplicity) that the probability of kill of the ASAT is 1.0.

Thus, for example, if the availability of BP satellites were 0.1, the cost of the BP satellite would have to be less than one-tenth that of the ASAT for the U.S. to even begin to have a cost advantage.

Specifically, if the BP satellite cost $2 M, the ASAT could cost as much as $20 M, and the Soviets would still break even. However, it seems likely that a small non-nuclear ASAT would cost under $0.5 M. Thus, the cost exchange ratio would probably be more than 40:1 in favor of the attacker. If the ICBMs have to be attacked in boost-phase, the availability of the interceptors would probably drop to 1 or 2 percent, and the cost exchange ratio could be as much as 200-400:1 in favor of the attacker.

NUCLEAR WARHEAD

One final note on the general war scenario. It was assumed that the ASAT carried a non-nuclear warhead. However, a nuclear warhead might also be cost effective. For example, a 200-kT nuclear warhead might weigh less than 300 lb and a warhead with a yield of a few kilotons might weigh less than a 100 lb.[37] The small-yield weapon probably could be delivered to an altitude of 500 km by an inexpensive 800-lb ASAT rocket (Sec. 3). A missile the size of the Patriot air defense missile could deliver the larger warhead to this altitude at a cost of around $250,000 (including the guidance system).

The cost of the nuclear warhead is uncertain and depends to a large degree on the availability of nuclear material (plutonium and enriched uranium). If the material came from the current stockpile or from retired warheads, the cost would be quite low. But even a completely new warhead with new nuclear material is likely to cost at most a few million dollars, considerably less than the $20 M the Soviets could afford to spend (for ER=1).

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[37]T. B. Cochran, et al, *Nuclear Weapons Databook, Vol. I,* (Cambridge, MA: Ballinger, 1984). If the hardness of the BP satellite were 10 cal/cm^2, the lethal radius would be 11 km for a 200-kT warhead and 2 km for a 5-kT warhead.

4.3 WAR OF ATTRITION

The exchange ratio in a war of attrition can be approximated by the relative cost of an orbiting BP satellite vs. the cost of the ASAT,[38] i.e,

$$ER \approx S/A.$$

Thus, if the BP satellite cost \$2 M, the Soviets could afford to spend up to \$2 M on the ASAT and still break even.

Since it appears that S would be greater than A for a small, non-nuclear ASAT (by a factor of at least 4), a war of attrition would also seem to favor the attacker.[39]

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[38]Unless the BP satellites are attacked as they are being deployed, this probably underestimates the advantage of the attacker since it ignores the initial cost of the entire satellite constellation. In effect, it assumes that all the BP satellites would have to be destroyed to negate the effectiveness of the defense (see App. C).

[39]A nuclear warhead might also be cost effective if the cost of the warhead could be held to about the cost of the Brilliant Pebble, which could be possible if there were an abundance of nuclear material. (In practice, even a somewhat more expensive warhead might be cost effective -- see App. C.)

5 DEFENSE OF BP SATELLITES

To be cost effective, it would appear that the BP satellite would have to utilize some inexpensive countermeasure to protect the satellite. The most widely discussed approaches to countering an ASAT threat will be examined in this section.

5.1 MANEUVER

If the BP satellite does not maneuver, the ASAT could use an inertial guidance system to bring the warhead close enough for the on-board IR sensor to acquire and home on the satellite. However, if the BP satellite can detect the launch of the small ASAT rocket,[40] it can maneuver out of its previous flight path (presuming it has extra fuel on board). Whether the MHV would be able to detect the change in the BP satellite orbit at long range and make the appropriate corrections in flight path depends upon the sensitivity of its sensors. For example, the BP missile warhead is evidently supposed to be able to detect an ICBM's small, cold post-boost vehicle (PBV) at quite long ranges. Similar capabilities on the MHV could allow for a timely diversion to a new intercept point.

If on-board detection of the change in the BP satellite's flight path were not possible, the Soviet would have to rely on external sensors for detection and to command guide the ASAT to the corrected intercept point. For example, it has been reported that current U.S. radars "can track small objects and follow orbit changes with high precision out to distances of more than 1000 miles; in fact, they have successfully located a Hasselbland camera and an astronaut's glove in orbit."[41]

The Soviets have a number of radars that might be suitable for the task. For example, they continue to update and modernize their ABM system around Moscow. This is a two-tiered system with long-range exo-atmospheric Galosh missiles and endo-atmospheric Gazelle missiles supported by various associated engagement, guidance, and battle management radar systems including the new, large, four-sided, multifunctional, phased-array Pill Box radar at

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[40]This is not a forgone conclusion since the rocket could be quite small. If a rail or gas gun were used to launch the MHV, the launch is unlikely to be detected.

[41] Report of the Technical Panel on Missile Defense in the 1990s, Marshall Institute, 1987.

Puskino north of Moscow. This type radar can simultaneously track large numbers of targets, detect orbit changes, and guide interceptors to new intercept points.[42]

In addition to the Moscow system, there is a ballistic missile warning system. For example, there are 11 large Hen House early warning radars at 6 locations on the periphery of the Soviet Union. This older network of radars has been upgraded, and it is quite capable at providing target tracking data on BP satellites. In addition, the Soviet are now in the process of completing the installation of 8 large phased-array radars (LPARs) -- similar to (but larger than) the Pill Box radar -- to give an almost complete ring of coverage to the Soviet land mass. "All LPARs ... have the inherent capability to track large numbers of objects accurately. Thus, they ... have an inherent technical potential, depending on location and orientation, of contributing to ABM battle management."[43]

In short, it seems likely that a change in the satellite's flight-path could be detected by Soviet radars in time for the ASAT warhead to be command-guided to a new intercept point. In a war of attrition, the Moscow system could direct the engagement. In a general war, it is likely that the peripheral LPARs could be used, with the ASATs being based in the northern regions of the Soviet Union.

As noted in Sec. 3.3, the ASAT rocket chosen in this study was about 3.5 times the required size in order to allow for the possibility of added fuel for maneuvering.[44] Thus, the extra fuel for maneuvering is already included in the cost of the ASAT. At any rate, since the BP satellite is likely to weigh several times more than the ASAT homing vehicle, any fuel weight penalty should favor the attacker.

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[42]Ashton B. Carter and David N. Schwartz, eds., *Ballistic Missile Defense* (Washington,D.C.: The Brookings Institution, 1984), p. 69.

[43]Soviet Military Power,1989 (Washington,D.C.: GPO, 1989), p. 58.

[44]A fuel mass equal to half the mass of the homing vehicle would allow a divert velocity of about 1.2 km/s. With this capability, the homing vehicle could be diverted 120 km in about 100 s.

5.2 DECOYS IN PEACETIME

The U.S. might deploy a number of decoys with each BP satellite in an attempt to hide the real satellite among the decoys. If the decoys were deployed in peacetime, the success of this tactic when the satellite and decoys are in a relatively low orbit is problematic. For example, if the decoys have some velocity relative to the satellite, they will eventually drift away (unless they are tethered to the satellite -- which could prove to be complicated). Even if the deployment problem can be overcome, the Soviets will probably have techniques available that could discriminate the satellite from the decoys.

As noted above, Soviet phased-array radars should be quite effective at tracking objects in low orbits. Since over time the behavior of the light decoys will differ from that of the satellite,[45] radar should be able to discriminate the decoys from the satellite.

Another approach might be to use ground-based lasers.[46] A special American Physical Society study group concluded that "it appears that several tens of kJ of laser energy will produce sufficient velocity changes to permit discrimination of lightweight (~1 kg) balloon decoys ($\Delta v \approx 10$ cm/s)."[47] A ground-based laser with an average power of about 100 kW should be able to discriminate about 25 decoys in 500 s.[48] Alternatively, since time would not be critical, a 50-kW continuous wave laser could probably be used to vaporize a 1-kg decoy at the rate of 1 decoy every 100 s.[49]

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[45]Even if the satellite were dormant, the different drag coefficients of the two types of objects should produce noticeable changes in their orbits over time.

[46]The Soviet laser program involves over 10,000 scientists and engineers and more than a half-dozen major research and development facilities and test ranges. According to the Defense Department, the Soviets already have ground-based lasers that have some capability to attack U.S. satellites and could soon have prototypes for ground-based lasers for defense against ballistic missiles. Soviet Military Power,1987 (Washington,D.C.: GPO, 1987), p. 51.

[47] "APS Study: Science and Technology of Directed Energy Weapons", *Rev. Mod. Phys.*, Vol. 59, No. 3, Part II, July 1987, p. S160.

[48]Based on *ibid.*, p. S163. This assumes an atmospheric loss factor of 10 and a 1000 cm^2 spot at a range of 500 km. A total of 5 MJ would be delivered to the targets in this time (200 kJ per decoy).

[49]Based on *ibid.*, p. S164. This assumes an atmospheric loss factor of 10 and an energy deposition of about 500 kJ per decoy (to destroy about 1/2 the decoy's surface).

Thus, with the use of remote sensors, it is likely that over some period of observation, the Soviets could (with high confidence) discriminate the real satellites from the decoys.

5.3 DECOYS AND MANEUVERING

Perhaps a more logical approach for the U.S. would be to wait until the satellite was under attack to disperse the decoys. Thus, once an ASAT launch was detected, the BP satellite would launch some number of decoys (N) and make a velocity change in the satellite. If this velocity change were *unobservable,* there would be N+1 plausible targets for the Soviets to examine and attack. If the Soviets could not discriminate the real target from the decoys during the time-of-flight of the ASAT, the probability of an ASAT attacking the real target would be $(N+1)^{-1}$. For example, if N=30, the probability of the satellite being killed would be only about 0.03.

WAR OF ATTRITION

Despite the advantage to the Soviets of low BP satellite availability in a general war, it seems much more likely that they would pursue a "peacetime" war of attrition if the U.S. deployed a space-based defense. They clearly would not want to be in a position where the U.S. could (in a "first strike") attack Soviet strategic forces and handle the surviving forces with its space-based and ground-based defense system -- any more than the U.S. would want to be in that position. Thus, they could decide that their best (or "least worst") course of action would be to try to negate the critical space-based component of that defense by shooting down U.S. weapons orbiting over Soviet airspace.

In a war of attrition, there might be several relatively low-cost ways to defeat a defense that deployed decoys when attacked:

<u>Discrimination</u> With a ground-based laser, it might be possible to distinguish the decoys from the satellite (by measuring the change in velocity due to the impulse of the laser). With a 1-MW laser, about 25 decoys could be discriminated in 50 s, which should provide sufficient time for the ASAT to divert to the real target. (See Sec. 5.2.) Larger numbers of decoys would require more powerful or more numerous lasers.

Another possible approach would be to use pulse-Doppler laser radars that can generate high-resolution images and obtain precise measurements of an object's motion in space. Recent U.S. experiments indicate that observation during deployment could allow the Soviets (if they had similar technology) to distinguish the decoys from the actual BP satellite.[50]

Early Launch Since the BP satellite must do its own tracking, if it did not "see" the launch, it would not know it should deploy its decoys and maneuver. Thus, if the ASAT were launched before the BP satellite was in view, the BP satellite could possibly be attacked without it having taken any countermeasures. This might require a slightly larger ASAT rocket to fly down range to intercept the BP satellite, but it should still be relatively inexpensive (see Sec. 3.3).

In principle, the BP satellites in view of the launch (assuming that they could detect the launch of a very small ASAT rocket[51]) could relay information to up-stream BP satellites to allow them to deploy their decoys. Of course, this relay tactic would probably not be effective if the Soviets attacked the BP system as it was being deployed, since there might not be enough BPs to give over-the-horizon warning. At any rate, it is not clear that the defense could pinpoint which particular BP satellites would be under attack. Thus, many BP satellites might erroneously deploy their decoys.

Flushing the Decoys In a war of attrition, the attacker would have an even more straightforward tactic. When the Soviets fire an ASAT, the targeted BP satellite is compelled to deploy its decoys and maneuver. The Soviets (being in no hurry) could then examine the decoys over time, discover the real target, and then launch another ASAT to destroy the BP satellite. The first ASAT need not even contain a real warhead, since its only function would be to flush the BP satellite decoys. The cost of the ASAT and an "ASAT decoy"[52] would be considerably less than the cost of the satellite and its decoys.

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[50] Reportedly, on March 29, 1990, a carbon-dioxide laser using an inverse synthetic aperture technique successfully demonstrated this discrimination capability when observing the deployment of an RV decoy at a range of 500 mi. *Aviation Week & Space Technology*, April 23, 1990, p. 75.

[51] If a rail or gas gun were used to launch the MHV, the launch almost certainly would not be detected.

[52] The ASAT decoy might cost well under $100,000.

A nuclear ASAT that cost about the same as a Brilliant Pebble might also be cost effective. A relatively inexpensive "ASAT decoy" could be used to flush the BP decoys, and the nuclear ASAT could be used as the follow-up missile for the kill.

GENERAL WAR

In preparation for the possibility of an eventual general war, the Soviet might launch ASAT decoys at the BP satellites in peacetime. No attack on the satellites would actually take place, but the satellites would not know this beforehand and thus would be compelled to deploy their decoys. Once the satellites were stripped of their decoy defenses (over time the Soviets could discriminate the decoys from the BP satellites), the BP satellites would be at the same disadvantage as previously noted. Flushing the decoys need not be a prelude to an immediate attack, but just a tactic to weaken the defense. Indeed, the attack might not occur for years, if at all.

If, instead, the Soviets had to attack each decoy with an ASAT warhead, it obviously would be much more technically complicated and much more expensive. For example, if the U.S. deployed a great number of decoys with each BP satellite, some way would have to be found to assign ASAT warheads to targets.

It is possible that an inertial guidance system could be used to get the ASATs into the acquisition "basket" of the cloud of decoys and the BP. One large ASAT rocket could be used to deliver the required number of MHVs (approximately equal to the number of decoys) to the threat cloud. However, assigning targets would be complicated. One possibility would be to use some sort of allocation scheme similar to the one used by the BP satellites to decide which ICBM targets to attack. This might require some sort of communications between the MHVs.

Alternatively, the MHVs could be command-guided to individual targets since they would be operating in view of the Soviet LPARs. Whether this might overwhelm the data handling capability of these radars is uncertain and unanswerable at this level of analysis and available information.

In the following, we will assume that some way to assign MHV warheads to individual targets can be found. Thus, if (as part of a general war) the Soviets chose to attack the decoys, the cost exchange ratio (ER) would be given by[53]:

$$ER = \frac{S+nD}{\beta NA}$$

where

S = cost of the BP satellite (including launch costs)

n = number of decoys per satellite

D = cost of a decoy (including launch costs)

ß = availability of satellites

N = number of Soviet ASATs fired at a satellite and its decoys

A = cost of ASAT.

If each object (decoys plus BP satellite) is attacked by an ASAT, then N=n+1 and

$$ER = S/[\beta A(n+1)] + nD/[\beta A(n+1)] \quad .$$

If we assume S=\$2, A=\$0.5 M,[54] and D=\$0.0067d M, where d is the mass of the decoy (and its dispenser) in pounds[55], the exchange ratio becomes

$$ER = 4/\beta(n+1) + 0.013dn/\beta(n+1) \quad .$$

The weight of a BP decoy is very uncertain at this point, but it could possibly range from between 1 lb to 1 kg.[56] If we assume that each decoy (and its share of the dispenser) weighed 1 lb, and if the

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[53]Again, assuming that the probability of kill of the ASAT is 1.0.

[54]Against a BP system with many decoys, the Soviets would probably use a larger ASAT missile to deploy many MHVs instead of one. This could lower the cost of each delivered MHV. Nevertheless, we will continue to use a cost of \$0.5 M.

[55]This ignores the cost of the decoy and its dispenser and assumes a launch cost of \$6700/lb (corresponding to the use of an upgraded Titan IV launcher).

[56]To approach the lower limit would require the use of some sort of simple balloon. A replica decoy might weigh about 1-2 kg. "APS Study: Science and Technology of Directed Energy Weapons", *Rev. Mod. Phys.*, Vol. 59, No. 3, Part II, July 1987, p. S155.

availability of the satellites were 0.1, the exchange ratio would equal 1 if there were about 45 decoys per satellite. Thus, if there were 10,000 satellites, 450,000 decoys would have to be deployed at a cost of over $3 B. If the decoy weighed 1 kg, about 55 decoys per satellite would be required to break even economically. Hence, a total of 550,000 decoys would be required, and the cost to deploy the heavier decoys could exceed $8 B.

These calculations are based on an exchange ratio of 1, which means that all the decoys would be attacked and that none of the BPs participating in the engagement (0.1 of the total constellation of satellites) would survive. For the space-based defense to be effective, the U.S. would have to provide considerably more decoys than the number of attacking ASATs.

For example, assuming that the U.S. and the Soviet Union spend the same amount of money, to make as much as half of the participating BP satellites survivable would require that the U.S. deploy about 110 decoys per satellite if the decoys weighed 1 lb each.[57] If a decoy weighed 1 kg, about 185 decoys per satellite would be required (at a deployment cost for the SBI system of over $27 B). In general, higher levels of survivability become very expensive. For example, to achieve 70 percent survivability would require 2800 decoys per satellite if each decoy weighed 1 kg. These values are obviously very sensitive to the various costs involved and hence should just be considered indicative of the kinds of problems faced in designing a survivable system.

Thus, whether this tactic would be economically feasible remains an open question. However, even if feasible, the utility of a space-based system that is only 50 percent or so survivable would seem to be limited. For example, if $\beta=0.1$, about half the Soviet warheads might escape even without Soviet countermeasures (because in many cases the PBV would be attacked with only a few RVs on board). If in addition only half the BP interceptors survived, perhaps 75 percent of the Soviet RVs and RV decoys would escape this layer of the defense. This could place a very heavy burden on the other layers.

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[57]For the above assumptions and with ER=1, n=(39+Ps)/(1-Ps-0.13d), where Ps is the probability of survival of the satellites.

Of course, if the defense were designed to attack the missiles only during boost-phase, the availability of the BP interceptors would be reduced to around 0.01-0.02. In that case, the exchange ratio might always favor the attacker and decoys would not be a cost effective tactic for the U.S.[58]

5.4 ACTIVE DEFENSE OF SATELLITES

Another possible U.S. countermeasure is an active defense using small rockets (DSATs). These rockets would be similar to the SBIs except they could be smaller since the required velocity could be more like 2 km/s instead of 6 km/s. Ideally, a DSAT might be as small as 50 lb (including its share of the weight of a multi-missile launch platform). However, there are a number of difficulties with the DSAT approach.

The ASAT warhead would be very small and cold (it could be shielded during the boost-phase), and thus difficult to detect. Hence, the probability of a missile "leaking" through the defense could be high for multiple ASAT attacks.[59]

However, if we ignore leakage, there is the matter of cost. Since in the BP system there are no large tracking satellites, the DSAT would have to be about as sophisticated as the SBI, and thus about as expensive. Therefore, it might be more logical to proliferate SBIs -- except we have seen that this would not be cost-effective.

If the DSAT weighed about 50 lbs and the ASAT warhead about 33 lbs, there would clearly be a weight advantage for the attacker. If the lift advantage of the ASAT and the availability of the satellites were taken into account, the advantage would be about 100:1 in favor of the ASAT. In a war of attrition (where absenteeism

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[58]For the assumed costs and for $\beta=0.02$, ER will always be greater than 1 if $d>1.54$ lb.
[59]If the U.S. defense had no "shoot-look-shoot" capability (perhaps because of difficulty in attack assessment or in re-acquiring the missed target), leakage could be severe even if the DSAT had a high probability of kill. For example, if the DSAT and the ASAT each had a combined reliability/probability of kill of 0.9, then the survivability of the BP satellite is given by $P_S=(0.91)^N$ where N is the number of ASATs fired at the satellite. For N=10, Ps= 0.39 and for N=30, Ps=0.06. The Soviets could probably afford 40 or more ASATs in a general war even if the cost of the DSATs is ignored (Sec. 3).

is not a factor), the advantage would be about 10:1 in favor of the attacker.

In addition, the Soviets could deploy cheap, light-weight ASAT warhead decoys. If the U.S. had to attack each decoy, this would further increase the Soviet cost advantage (and perhaps quickly exhaust the defense).

6 CONCLUSIONS

In a general war, if the BP satellite does not have its own defenses, the condition for the space-based defense being economically viable is that the cost of the satellite must be less than the cost of the ASAT reduced by the satellite availability, i.e., $S<\beta A$. For a defense that includes both those SBIs that can attack the boosters and those that can attack only the post-boost vehicle, S would probably have to be less than 0.1A. For a defense designed to attack the boosters before any RVs had been deployed, S would probably have to be less than 0.01A or 0.02A.

Although, the BP is small and relatively inexpensive compared to other space-based concepts, it does not appear feasible to meet this requirement when the ASAT carries a small non-nuclear homing device. Even a larger ASAT missile carrying a nuclear warhead would very likely be economically feasible for the Soviets.

If there were a war of attrition, the situation would be improved for the U.S. in the sense that now the exchange ratio could be made to favor the U.S. if $S<A$. However, again, it does not appear that a BP satellite could meet this condition against a small, non-nuclear ASAT.

Thus, the primary conclusion of this paper is that the BP approach to SBIs, while perhaps better than other SBI systems, will not be economically competitive, unless some relatively inexpensive countermeasures to defeat the ASATs can be found.

A preliminary examination of the most widely discussed countermeasures -- maneuver, decoys, and space-based defensive rockets -- was made. None of these approaches appears to be clearly economically advantageous.

Of course, at this stage, it is impossible to say that a more detailed analysis would not reverse this conclusion or that perhaps some other approach to countermeasures might not prove economically feasible. But the analysis does suggest that there could be a serious problem and that any future discussion of the design of the BP system should include and resolve the question of whether or not effective countermeasures against small, direct-ascent ASATs can be found.

APPENDIX A ORBITING VS. DIRECT ASCENT

Figures A-1 through A-3 compare the requirements for orbiting a payload vs. those to lift the payload to the same altitude with a direct-ascent rocket.[60] These curves include velocity losses due to thrust-atmospheric, gravity, and drag effects.

In this paper, the BP satellite is assumed to be in a 500-km orbit. In that case, the required launcher velocity to place the satellite in orbit is about 9.7 km/s. The velocity requirement for a direct-ascent ASAT at this altitude is about 3.5 km/s. If an ideal space launcher is used to orbit the satellite, the direct-ascent rocket would have about a 7 to 1 advantage. If the Space Shuttle were used for a 500-km orbit, the advantage to the direct-ascent rocket would be around 26 to 1.

BP interceptors might be able to attack ICBMs from a range of 2000 km or so. Thus, if the ASAT attack is a prelude to an ICBM launch (a general war rather than a war of attrition), the satellites would have to be attacked about 2000 km "upstream" from the ICBM bases. Most of the Soviet ICBM bases (particularly the SS-18s and SS-19s) are more than 2000 km from the northernmost parts of the Soviet Union. Thus, if the ASATs were placed in these regions, they could protect most of the bases by flying nearly "straight up" rather than having to fly far upstream to intercept the satellite. If new bases were required (and the cost amortized over all the ASAT missiles), this could increase the cost of each ASAT missile somewhat. Of course, since the ASAT missiles would be small, current navy ships operating in the Arctic might be used as launch platforms for many or all of the missiles.

Alternatively, the ASATs (using current military bases, but not co-located with the ICBMs) could fly upstream to intercept the satellites. A 5 km/s rocket could intercept the satellite at range well over 1000 km from its launch point. This would approximately double the required size of the ASAT rocket (growth factor $\approx$ 16) and reduce the ASAT's launch advantage over a satellite to about 3.4 to 1.

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[60]Derived from Jerry Frost, "Propulsion System Velocity Requirements and Payload Growth Factor for Circular Orbits and Direct Ascent Interceptor," R&D Associates, May 1984.

FIG. A-1 PROPULSION SYSTEM VELOCITY REQUIREMENTS

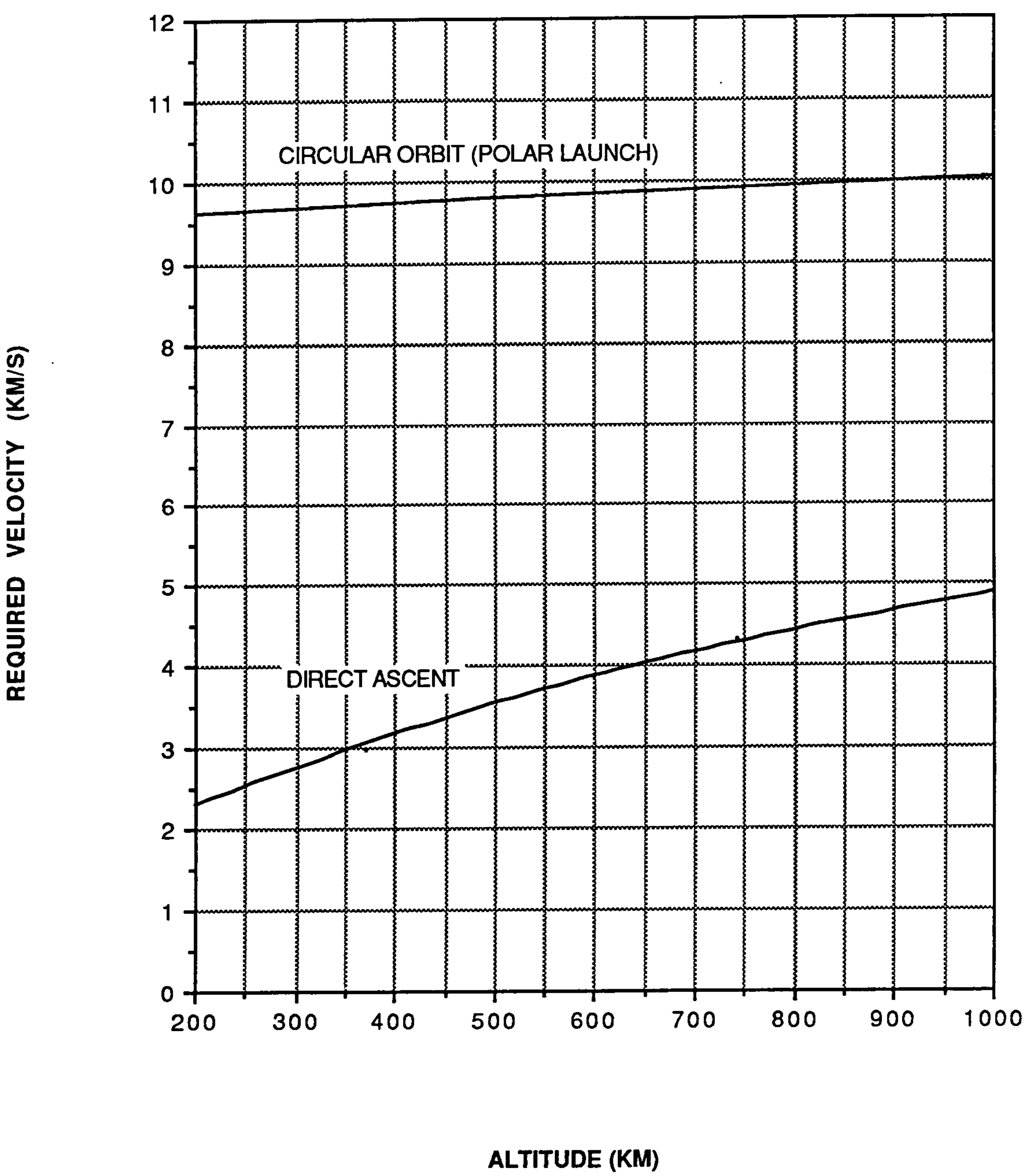


FIG. A-2 PAYLOAD GROWTH FACTOR

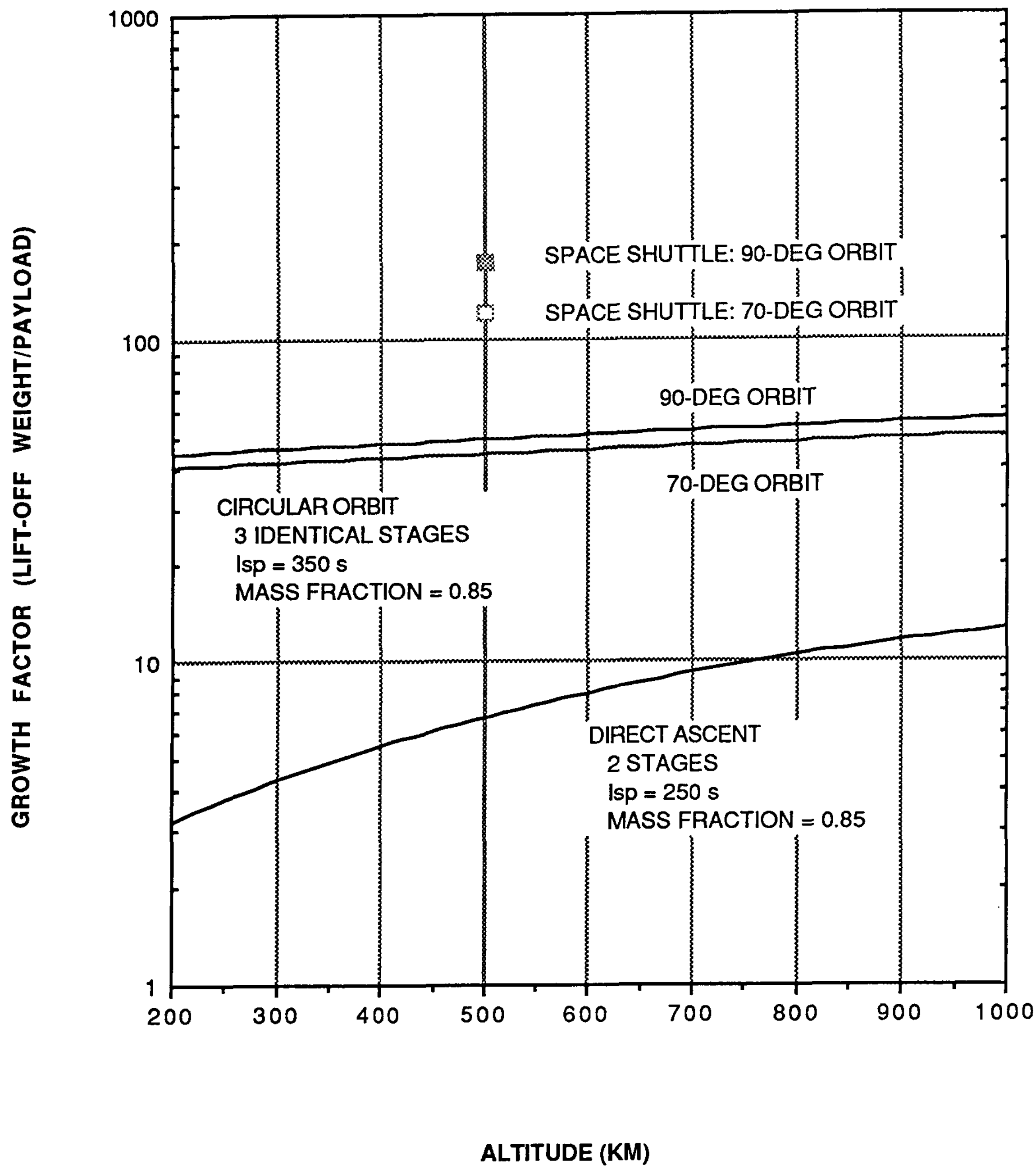
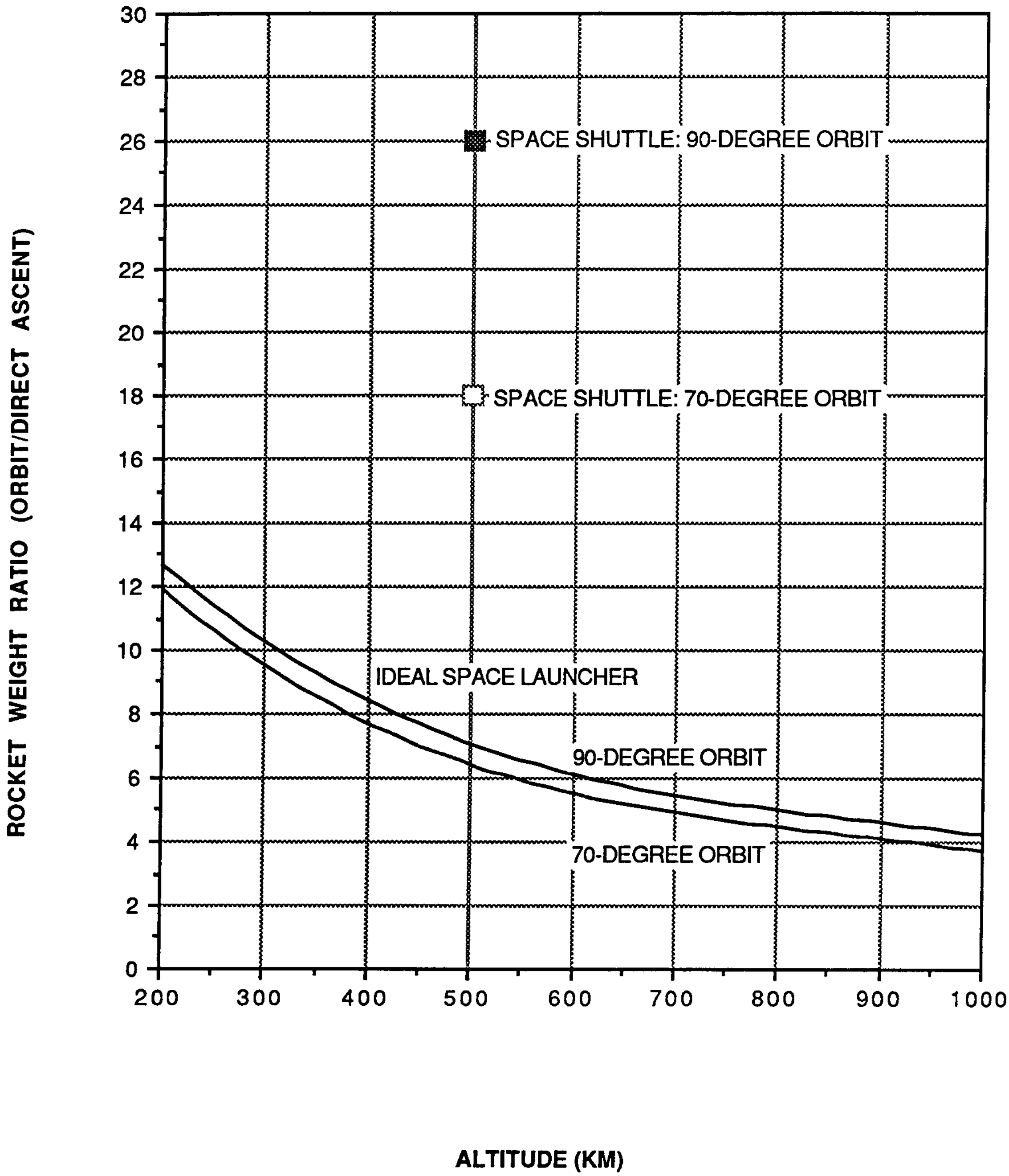


FIG. A-3 ROCKET WEIGHT RATIO



APPENDIX B SATELLITE AVAILABILITY

The availability of BP satellites to participate in an engagement depends on a number factors, including the velocity of the interceptor, the boost-phase flight time of the ICBM, how long the post-boost vehicle (PBV) takes to dispense the RVs, the size of the region in which ICBMs are based, the orbit of the satellites, etc. Cunningham[61] has made the following estimate of the participation (f) of 6-km/s SBIs against ICBMs based in a 1000-km launch region:

SYSTEM	BOOST PHASE			MIRV DEPLOYMENT	
	NO. MIRVS	TIME (S)	f (%)	TIME (S)	f (%)
CURRENT LIQUID	10-14	300	2.5	450	12.0
FOLLOW-ON LIQUID	14	240	1.7	300	5.6
SS-24	10	180	1.1	300	4.8
SS-25	1	180	1.1	- -	- -

In this calculation, it was assumed that some external sensor provided launch information to the SBI, allowing it to launch before it could actually "see" the ICBM. This would require other BP satellite to relay information to "over-the-horizon" BP satellites. Such a "pre-commitment" strategy could considerably complicate the problem of allocating particular BPs to particular ICBMs.[62]

Today, most of the Soviet ICBMs are carried on liquid-fueled SS-18s and SS-19s, although there are a growing number of solid-fueled missiles. The CIA[63] expects that by the mid-1990s over half the launchers of the Soviet ICBM force (carrying about two-thirds of the warheads) will be solid fueled (i.e., the SS-24 and SS-25). Most of the rest of the missiles will consist of follow-on liquid-fueled heavy ICBMs.

Thus, by the time the BP system could be in place, it is likely that the availability of the BP satellites might be only around 5

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[61]C.T. Cunningham, "The Space-Based Interceptor", in *Nuclear Arms Technologies in the 1990's,* ed. Schroeer and Hafemeister, American Institute of Physics, Washington D.C., 1988.

[62]If this strategy proved infeasible, the table would overestimate the availability of BP satellites to participate in the engagement.

[63] Soviet Military Power,1987 (Washington, D.C.: GPO, 1987)

percent of the total force (or less), if most of the ICBMs were deployed in a region 1000 km long. If the ICBMs were at sites all across the Soviet Union, the availability might be twice this amount.

Of course, this estimate includes those BP interceptors that can only reach the PBVs and not the boosters.[64] If a defense "shield" for the country is desired, the U.S. would very likely have to attack the booster before the PBV separates and starts dispensing RVs and decoys (see Sec. 2). In that case, the availability of BP interceptors might be only 1 or 2 percent.

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[64]Having the capability to attack the PBV could prove to be a formidable technical challenge -- but it appears to be a design requirement for the BP system.

APPENDIX C WAR OF ATTRITION

If the Soviets shot down each BP satellite immediately after it was put into orbit, the cost exchange ratio would just be the cost of the BP satellite divided by the cost of the ASAT.

If the Soviets waited until the BP system was in place, the economics could be somewhat different. Consider the case where there are 1000 Soviet ICBMs and 10,000 SBIs. If the Soviets can "punch a hole" in the defense by destroying 1000 SBIs, the 1000 ICBMs would be able to escape.

In a "peacetime" war of attrition, the Soviets would attack these 1000 BP satellites over some period of time. After the 1000 satellites were destroyed, the U.S. could refill the hole with new satellites. The Soviets would then have to shoot down the replacement satellites, and the cycle could be repeated any number of times.

The cost exchange ratio for a war of attrition is

$$ER = \frac{C_B + NS}{C_A + NA}$$

where

C_B = cost of the original BP constellation of satellites

N = number of new BP satellites deployed

S = cost of BP satellite (including launch cost)

C_A = cost to Soviets to "punch a hole" in the defense, and

A = cost of ASAT .

Again, using the same example, if the Soviets required 1000 ASATs to negate the defense, then the cost exchange ratio would be

$$ER = (10{,}000S + NS)/(1000A + NA)$$

$$ER = (S/A)(10{,}000 + N)/(1000 + N) \ .$$

If the BP satellites were not replaced, ER = 10(S/A), the answer obtained in a general war scenario. If all 1000 were replaced, the exchange ratio would be improved by a factor of about 2, i.e., ER=5.5(S/A). Of course, as long as S>A, the exchange ratio will always favor the attacker.[65]

MANEUVERING SATELLITES

It should be noted that if the BP satellites were fixed in their constellation, the boost-phase defense would be ineffective until the satellites were replaced. However, if the satellites carried extra fuel on board, they could reposition themselves to repair the "hole" created by the ASAT attack -- at the cost of a somewhat degraded defense. Once the satellites were replaced, the satellites would then have to reposition themselves again for an optimum distribution.

If the BP satellites had this capability and the Soviets wished to keep the defense system in a permanently degraded condition, it would have to expend more ASATs initially. For example, if a system degraded to 50 percent effectiveness were acceptable, initially the Soviets would have to destroy 5000 BP satellites. In that case, the exchange ratio would become

$$ER=(S/A)(10{,}000+N)/(5000+N).$$

After 1000 BP satellites had been replaced and attacked, the exchange ratio would be 1.8(S/A).

In summary, no matter how large the initial Soviet attack,[66] from Sec. 3, it would appear that S will be greater than A, and thus a war of attrition (when there are no U.S. countermeasures) will always favor the attacker.

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[65]Even if S were less than A, it would still take a number of cycles of attack and replenishment before the exchange ratio favored the U.S., unless S were very much less than A. For example, if S=0.75 A, N would be 28,000. That is, the Soviets could attack 28,000 replacement satellites before the exchange ratio would shift in favor of the U.S.
[66]In the extreme, shooting down all the BP satellites would give ER=S/A.