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Interaction of Strategic Defenses with Crisis Stability

Part I. Framework and Analysis

Los Alamos

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by

Gregory H. Canavan

ABSTRACT

Crisis stability indices calculated for two-sided strategic interactions are used to discuss the impact of boost and midcourse defenses. They largely suppress missiles, leaving bombers and cruise missiles to deliver the bulk of restrikes. Boost-phase defenses are able to attrit missile attacks, but lack the preferentiality needed to defend specific targets. Midcourse layers could protect a significant fraction of forces; combined defenses could defend more. Results are sensitive to decoys and target sets.

I. INTRODUCTION

This note presents simplified calculations that pertain to the crisis stability of two-sided strategic interactions. They are interpreted in terms of approximate criteria for the stability of various combinations of offensive and defensive forces. The results are examined for sensitivity to model and deployment parameters, some of which are strong. The issue is the extent to which stability indices are shifted by the deployment of boost or midcourse defenses.

For modest boost-phase layers, intercontinental ballistic missiles (ICBMs) play little role in first strikes, let alone second; heavy ICBMs play none. SLBMs are attritted harder even when clustered before launch; they contribute only against small boost-phase defenses. For large defenses the contribution from ICBMs and submarine launched ballistic missiles (SLBMs) is an order of magnitude less than that expected from bombers and cruise missiles. The main role of defenses would be to increase the survivability of the bombers and cruise missiles, which would deliver the bulk of the restrike. Stability indices would then not be changed greatly if the ICBMs and SLBMs were deleted and the midcourse defenses used to defend the bombers.

Boost-phase defenses are unable to attrit missile attacks enough to save significant numbers of undefended fixed targets. Attrition is adequate, but without preferentiality they cannot usefully convert attrition into targets saved, which undermines their contribution to stability. Midcourse layers could at all levels protect a significant fraction of ICBMs due to their preferential operation. Combined boost and midcourse defenses could defend a large fraction.

Without defenses, bomber restrikes are critically dependent on alert rates; with defenses that strong sensitivity is largely removed. Defending bombers is a key interaction for promoting stability, which boost and midcourse defenses should be able to perform as well for bases as for missile silos.

Relevant numbers of decoys could reduce composite stability indices by large factors. Saturating midcourse defenses with decoys would collapse the combined stability curve to that of boost-phase only defenses. If force levels were reduced without reducing the target sets, stability indices would appear to degrade because value objectives were reduced, even though fewer weapons could fall on either country. For them to be independent of target set it is necessary to reduce the targets held at risk along with the strategic forces available or to negotiate away value targets in proportion to strategic forces as they are reduced. Otherwise, the accepted formalism indicates smaller offensive deployments are less stable and larger ones more stable just due to the scaling of the damage curves. It appears that the issues most in need of further work are the impact of decoys on combined defenses and the possibility of a parallel build-down of offensive forces and build-up of defenses in cooperative or independent deployments.

II. EXCHANGE MODEL

The model used is a two-sided, sequential, deterministic description of U.S.-Soviet exchanges, which parameterizes each side's offensive and defensive force levels and effectiveness. It allows either side to strike first or second and uses the ratio of their costs as an indicator of the pressures to do so in crises, i.e., periods of heightened tension and the potential use of force. In it, boost-phase defenses are treated as non-preferential, i.e., random and subtractive in operation, as is the case for current boost-phase defenses against land- and sea-based launchers. Midcourse interceptors are treated as preferential and of long range. Treating them as adaptive would increase their performance slightly, but would not be consistent with the availability of sensor and control nets in the near term, the principal focus of this note.[1]

SLBMs are assumed invulnerable before launch, but are thereafter attritted by appropriate fractions of boost-phase defenses and the full set of midcourse defenses. Once airborne, aircraft are assumed invulnerable to boost and midcourse defenses. Their prelaunch survivability is calculated explicitly as a function of defense size and disposition; penetrativity is treated parametrically.

In the model either side could strike first, which would be followed by the other's restrike. The costs to both sides for each alternative are then evaluated and combined into a single crisis index that measures the relative costs of striking first or second. The current offensive deterrence configuration is by this measure and most others, quite stable. The primary issue addressed here is the extent to which these stability indices are shifted by varying numbers of boost or midcourse defenses.

The model is described in Appendix A. The offensive forces, essentially START-constrained mixes and levels of missiles and aircraft, are described in Appendix B. Defensive forces, SDI phase 1 mixes of boost and midcourse defenses whose overall levels are varied parametrically to study sensitivities and phased deployments, are described in Appendix C. Appendix D discusses the optimal allocation of penetrating weapons between damage limiting and value targets; Appendix E. discusses the optimal allocation of defensive interceptors against them.

The model is basically a deterministic calculation of sequential exchanges followed by an evaluation of the resulting strikes on value targets, an assessment of the costs for imperfect damage limitation or value strikes by either side, and a calculation of a resulting stability index which collapses both sides' strike and cost information into a single number. It does not necessarily determine whether either side would strike; that probably depends more on psychological factors than on rational calculus,[2] but it does reduce complicated outputs into a readily manageable index, whose construction is consistent with the logic used for U.S. targeting and assessment and Soviet evaluations of the correlations of forces before and after strikes.[3]

III. COSTS

To provide some indication of the stability of different defensive configurations, it is useful to introduce a measure of the costs associated with striking from or being struck in those configurations. Given the difficulty of comparisons, dollar costs are almost meaningless. The operative currency is damage to self and other, and the objective is to prevent the former and retain the ability to inflict the latter. The budgets required for the forces are secondary, particularly for strategic forces, for which costs are a small fraction of defense budgets, let alone gross national products.

A simple measure of damage can be based on approximate expressions for the value destroyed as a function of the number of RVs that arrive, or the number of designated ground zeros destroyed, which can be represented by

$$D(R) = 1 - \exp(-k \cdot R), \tag{1}$$

where R is the number of RVs delivered on value targets, and k is a parameter that characterizes the number and distribution over value over the targets. For R small, $D \approx kR$, which corresponds to the summation of many targets of roughly equal value, e.g., missiles, bomber bases, garrisons, etc. For R large, $dD/dR = k \cdot \exp(-kR) \rightarrow 0$, which reflects the lower value of secondary targets and the large number of weapons needed to destroy some primary ones.

Value is taken here to be embodied largely in projection forces, i.e., in the means to maintain or extend power, which are the likely causes of conflict as well. Cities, which are loosely identified with value by some, constitute a small fraction of these value targets, which could be dispatched more efficiently by other means once the exchanges treated here were completed to determine who would do the dispatching. Value includes alternate bases, command, control, and communication (C^3), conventional forces, points and ports of embarkation, etc., which are numerous. For the U.S. a simple count of bases indicates that $\approx$ 85% of value is contained in $\approx$ 2,000 targets, which in terms of the parameters of Eq. (1) corresponds to $k \approx -\ln(0.15)/2{,}000 \approx 0.001$.

The Soviet Union has a similar damage function or distribution of value over facilities denoted by

$$D'(R) = 1 - \exp(-k' \cdot R), \tag{2}$$

where primes are used to denote Soviet parameters. This prime-unprime notation is used throughout to simplify derivations and to avoid having to repeatedly label one side or the other as the putative aggressor in an exchange that should never happen if crises are properly prepared for. The Soviet Union has somewhat larger projection forces than the U.S., which in part reflects their continental position and in part their numerous, restless neighbors and provinces. About 90% of Soviet value appears to be in ≈ 4,000 targets, which corresponds to $k' \approx 0.0006$.

As noted above, dollar cost comparisons are so difficult as to be almost meaningless.[4] Moreover, the costs for strategic systems are a small fraction of the cost of either side's budget, and the cost-effectiveness of destruction by nuclear missiles is so high as to make cost an insensitive measure of actual or potential destruction.[5] The costs used here are the real physical units of destruction that could be done to one or the other by specified strategic forces; dollar costs could be tallied later.

The objective, however, is not just inflicting damage, but satisfying one's national goals and denying the other's. Those goals are taken to be limiting damage by the other's attack to the extent possible and inflicting enough damage on the attacker to reduce or remove his ability to capitalize on his attack. These goals are logical and obvious, but they can and do act at cross purposes, so it is necessary to render them commensurate. The damage functions discussed above are a sound basis for constructing cost functions, but they can be combined in a number of ways, reflecting the ultimately subjective evaluation of how much damage is acceptable. The cost function adopted below to interpret the calculations is[6]

$$C_1 = D(R_2') + L\cdot[1 - D'(R_1)], \qquad (3)$$

which states that the cost to unprime of striking first is the damage done to him by prime's incompletely suppressed second strike, R_2', plus the portion of the desired damage that unprime is not able to inflict on prime by his first strike, R_1. The parameter L reflects the relative importance given to these two functions by unprime. The first term is obvious; the second less so. It reflects the fact that offensive weapons can be used to reduce the other's ability to continue war or seize recovery assets in other theaters--not just to destroy cities.

The combination of terms in Eq. (3) is not unique; products or powers of the damage functions could be combined rather than their linear combination. The results below are sensitive to, but not driven by, this choice of cost functions. A weighted sum of damage limitation and counter-value costs seems simplistic given their differing natures and goals, but the analysis below and its integral indices is not sensitive to the choice of function or to the specific value of L chosen. Using Eq. (2), Eq. (3) gives

$$C_1 = 1 - \exp(-k \cdot R_2') + L \cdot \exp(-k' R_1) \tag{4}$$

as unprime's cost for striking first. Conversely, if unprime waits, and prime strikes first, the cost to unprime for striking only in retaliation is

$$C_2 = 1 - \exp(-k \cdot R_1') + L \cdot \exp(-k' R_2). \tag{5}$$

The equations for C_1' and C_2' follow by conjugation, i.e., by replacing primed and unprimed symbols.

From the form of these equations it follows that if unprime strikes first, soundly, and from good defenses, R_1 is large and R_2' small, so that from Eq. (4), $C_1 \rightarrow k \cdot R_2'$. If prime strikes first and soundly, $C_2 \rightarrow 1 + L$. The ratio of these costs is

$$C_1/C_2 \approx k \cdot R_2'/(1+L). \tag{6}$$

Since the numerator is small, and the denominator can be large, the ratio of the costs for striking first to those for striking second can appear to be small, which would seem to provide an incentive for striking first in a crisis. This apparent pressure is not confined to this model; it appears in modified form for other cost metrics. It rests on little more than an intuitive notion of relative risks and the monotonically increasing damage functions used. This sensitivity is explored further in the following sections.

IV. CRISIS STABILITY INDEX

The index used below is an extension of that in Eq. (6), which is based on the intuitive relevance of the ratio of the cost of striking first to that of striking second as an indicator of how likely one is to strike at all. That combination can be obtained from a simple derivation, which associates this ratio with the likelihood of initiating interaction,[7] but no such association is needed here. Plausibility is enough, given the ultimately subjective evaluation of the costs. If the relevance of the ratio of the costs is plausible for one side, it should be about as plausible for the other, which provides an index for prime as well.

Then it only remains to combine the indices. A simple way to do so is to take the product of the indices of either side to arrive at

$$Q \equiv (C_1/C_2)(C_1'/C_2'). \tag{7}$$

While a derivation can again be given, the main point is that this is the bilinear combination of the simplest individual indices thought capable of representing each side's competing objectives. It has one other important property. For this index, if one side sees stability as low, so does the other, reflecting the obvious connection that neither side has an incentive to develop forces or act in a manner that could promote a crisis that could lead to a mutually annihilating exchange. Both sides have incentives to see the situation from the other's perspective. Stated in terms of the metric Q, each side should be able to see and willing to play the game from either side.

V. RESULTS

This section describes the results of calculations with the model. Their interpretation parallels but does not duplicate the derivations of scaling relations given in Appendix A, discussions of offensive and defensive forces in Appendices B and C, or the optimizations of attacks and defenses in Appendices D and E. The discussion assumes that prime strikes first and unprime retaliates, but the order is immaterial, and the opposite order must also be considered to construct a composite index of stability. Appendix A derives the equations for prime striking first, infers the equations for unprime striking first by conjugation, and then combines the results of the two derivations into the relevant cost and stability indices.

The equations in Appendix A are valid for arbitrary offensive and defensive force levels and performance, but the calculations below only treat START level offensive forces.

Sensitivities to components of those forces are noted in passing. The figures are drawn for equal prime and unprime boost-phase and midcourse defenses. Calculation of off-diagonal configurations is straightforward, but the START forces are roughly symmetrical, so there is less need to look for unsymmetrical deployments, and given the lowest cost denominator nature of previous arms control agreements, there is little likelihood that unsymmetrical deployments would be allowed.

A. First Strike

Figure 1 shows R_{1m}', which is the number of RVs from prime's first-strike ICBMs that penetrate unprime's boost-phase defenses. The abscissa is K, the number of SBIs in the unprime's boost-phase layer. The horizontal line at 3,000 RVs is for midcourse defenses only, which do not attrit RVs in boost. The next line is for both boost and boost plus midcourse defenses. For it, R_{1m}' falls from all 3,000 RVs penetrating at K = 0 to about 450 RVs at K = 4,000 SBIs. Boost-phase penetration scales on f, the fraction of SBIs available, which is $f \approx 0.2$, and the number of prime's heavy ICBMs, $M' = 266$, as $\exp(-fK/M') \approx \exp(-0.2 \cdot K/266) \approx \exp(-K/1330)$. For K = 4,000 penetration is $\approx \exp(-4{,}000/1330) \approx 5\%$, with which the Soviet heavy missile $m' \approx 10$ RVs per ICBM gives ≈ 130 penetrating RVs from heavy ICBMs. That is much less than the ≈ 470 RVs shown.

The rest come from the Soviet's 344 single missile mobile ICBMs. For them the SBIs' effective availability is a factor of 5-10 lower, so they essentially penetrate without attrition. It is not worthwhile for unprime to divert SBIs to them, so they essentially get a free ride for constellations of this size.[8] By 4,000 SBIs the mobile singlets constitute 75% of the penetrating ICBM RVs. For moderately large boost-phase layers, ICBMs play little role in the first strike, let alone the second; heavy ICBMs play none.

Here and below the number of midcourse interceptors, I, is set equal to I = K/4 unless otherwise stated. For the SBIs' $\approx 20\%$ availability against ICBMs in the near term, that means that there are always about as many ground-based interceptors (GBIs) engaged in midcourse as there are SBIs available in boost. Variations are studied in the following section. Boost-phase defenses are generally used as the abscissa. When they are used for midcourse-only defenses the abscissa in SBIs can be interpreted as meaning $I = K/4$ midcourse interceptors.

Figure 2 gives R_{1n}', the number of RVs from prime's first-strike SLBMs that penetrate unprime's boost-phase defenses. It assumes that all of the submarines are clustered in small areas before launch to improve their penetration of the boost layer. That is not current practice, but without clustering the SLBMs' contribution would be suppressed by about another order of magnitude and could be dropped altogether.[9] Under START the Soviets have 324 SLBMs, for which near-term SBIs have an availability of ≈ 0.1. If it is assumed that 1/4 of the SLBMs are in each of 4 clusters at launch, the SLBMS penetration is $\approx \exp(-0.1 \cdot K/80) \approx \exp(-K/800)$, which falls off rapidly for $K >$ 800 SBIs.

SLBM RVs still fall off faster than ICBM RVs because of the smaller number of SLBMs than ICBMs and hence weaker boost-phase penetration. At $K = 0$, R_{1m}' only exceeds R_{1n}' by 50%, but by 2,000 SBIs the ratio is a factor of 5, and by 4,000 the ratio is ≈ 100. Thus, SLBMs make a significant contribution only to first strikes against boost-phase defenses of less than $\approx$ 1,000 SBIs. For $K >$ 2,000 SBIs, even clustered SLBMs can essentially be ignored relative to the fast singlet ICBM RVs.

ICBM and SLBM RVs must pass through unprime's midcourse defenses before attacking missiles, bombers, and value targets. I prime midcourse interceptors attrit R RVs by roughly $\exp(-I/R)$, or $\approx \exp(-K/4R)$ for $I = K/4$. For $K = 1{,}000$, for which from Figs. 1 and 2, $R \approx 1{,}600 + 600 \approx 2{,}200$ RVs, the penetration $\exp(-K/4R)$ $\approx \exp(-1{,}000/4 \cdot 2{,}200) \approx 90\%$. But by 2,000 SBIs the attenuation is about $\exp[-2{,}000/4 \cdot (900+200)] \approx 63\%$, and by 4,000 SBIs it is $\exp[-4{,}000/4 \cdot (470+30)] \approx 14\%$, which is a small number compounding already massive attrition.

For small K the ICBM and SLBM attacks are overwhelming because of their massive numbers of unattritted RVs. By large K the SLBMs are gone and only a modest number of fast singlet ICBMs remain to be attritted, by another factor of ≈ 6 at 4,000 SBIs down to about $500 \cdot 0.14 \approx 70$ RVs, which is small compared to bomber and cruise missiles' contributions.

The allocation of ICBM and SLBM RVs and bomber weapons over targets is treated further below, but first it is useful to follow prime's restrike back through the defenses it faces.

B. Second Strike

Figure 3 shows M_s, the number of unprime ICBMs that survive an attack by ≈ 30% of $R_{1m}' + R_{1n}'$, assuming that they are defended preferentially by ≈ 30% of the $I = K/4$ midcourse interceptors at each value of K. The optimal choice of the fractions of penetrating RVs and defenses is discussed in Appendices D and E; these results are relatively insensitive to the specific value used. The top curve is for defenses with both boost and midcourse layers; the middle curve is for midcourse only. The bottom curve for a boost-phase only defense is essentially flat at $M_s \approx 0$.

Boost-phase defenses of these magnitudes are unable to attrit missile attacks sufficiently to save significant numbers of unprotected, fixed targets. Combined boost and midcourse defenses with 4,000 nominal SBIs could defend about 750 missiles, i.e., over 90% of them. Midcourse-only layers of 1,000 interceptors protect ≈ 150/800 ≈ 20% of the ICBMs; larger deployments could save proportionally more.

Figure 4 shows the number of surviving bomber bases under the assumption that they, too, can be preferentially defended by ≈ 30% of I from an attack by ≈ 30% of the penetrating RVs. The top curve holds for combined boost and midcourse defenses; the middle for midcourse; the bottom for boost-phase only. The ≈ 6 surviving bases at small K are just those on alert. The number surviving increases to 18 bases, or 90%, by 4,000 SBIs. The increase is due to successful preferential defenses. Without defenses bomber restrikes are critically dependent on their rates; with defenses that sensitivity is largely removed.

It is shown later that the protection of the bomber bases by defenses is a key interaction for promoting stability; thus, it should be noted here that it matters little to the boost-phase and midcourse defenses whether they defend bases or silos. Both have enough elements so that some can be intentionally sacrificed for preferentiality, and the defensive interactions would take place sufficiently far away from and above either target set to make their relative hardness a secondary consideration. Thus, the defense can meaningfully allocate midcourse interceptors between the defense of missiles and bombers, as discussed below and in the appendices.

The top curves of Figs. 3 and 4 show slow growth at small K, transition, and then saturation at large K. The reason is that for small K the threats are so large that the modest defenses are saturated. For intermediate levels such as $K \approx 2,000$, the boost-phase defenses reduce the threat to levels the midcourses can handle. For large K the additional gains from midcourse saturate as the number of survivors approaches the total target set. The curves have similar shapes because both represent preferential defenses against similar fractions of the threat.

Figure 5 shows R_{2m}, the number of unprime ICBM RVs that survive the attack and penetrate prime's boost-phase defenses. The top curve is for both boost and midcourse layers; the next for midcourse. The bottom for boost only is about zero everywhere. The curvature of the top curve is more pronounced than that in Figs. 3 and 4. The basic reason for its shape at low K is, as before, the saturation of the defenses by the unattrited attacks, followed here by the disproportionate attrition in boost of the few missiles left after prime's first strike. The sharper roll-off at $K \approx 4,000$ occurs because the gains from defense are saturating, but the losses to prime's boost-phase defenses continue to increase with K. If the curve was carried further, it would turn over altogether.

Comparing Figs. 3 and 5 is illuminating. At 2,000 SBIs the former gives 300 surviving missiles, which for the $m \approx 2$ RVs per U.S. ICBM means $\approx$ 600 RVs launched against the defense. Figure 5 shows that about 150, or 25% penetrate. At 4,000 SBIs about 700 missiles survive with $\approx$ 1,400 RVs, of which about 400, or 28% reach midcourse. Thus, at large K the larger number of surviving missiles launched helps penetration, but the larger number of prime boost-phase defenders encountered offsets it. Penetration scales as $\exp(-0.2K/M_s)$. For the conditions shown M_s increases no more rapidly than K, so the fraction penetrating remains constant and modest.

Note that 1,000 midcourse interceptors produce about half as many survivors as 4,000 SBIs at the high end and significantly more survivors at the low end. Note also that boost-phase-only defenses produce essentially no survivors across the whole range of SBIs shown. Their overall attrition is adequate, but without preferentiality they cannot usefully convert attrition into specific targets saved, which undermines their contribution to stability.

Figure 6 shows R_{2n}, the number of unprime SLBM RVs that penetrate prime's boost-phase defense. Like R_{1n}' in Fig. 2, it falls off exponentially. Comparing it to Fig. 5, however, shows that the strong suppression of the ICBMs tends to make the SLBMs' RVs more significant. They are clearly dominant below 2,000 SBIs, where they contribute $\approx$ 500 RVs as opposed to ICBMs' 150. At 3,000 they still contribute 200 to ICBMs' 350; even at 4,000 their contribution is about 10% of the total.

Unprime's RV restrike reaching prime's midcourse defense is the sum of $R_{2m} + R_{2n}$. From Figs. 5 and 6 it follows that for small K the sum is mainly that from SLBM RVs. For large K it is mostly fixed ICBM RVs, since unprime is given credit for no fast, mobile singlets. The rapid fall of the SLBMs and slow rise of the ICBM RVs produces a minimum for intermediate K, which is reflected in some subsequent curves.

Figure 7 shows R_{2p}, the number of RVs that penetrate both boost and midcourse defenses and strike prime's value. The top curve is for midcourse only; the next for boost only; the bottom for boost and midcourse. Midcourse only allows significant penetration. For boost or combined defenses, at small K, R_{2p} is essentially the SLBM RVs of Fig. 6, attritted by a small number of interceptors. For large K, R_{2p} is primarily ICBMs, since M_s reaches large enough values to penetrate. By 1,000 SBIs the midcourse attrition is still small; by 2,000-4,000 SBIs it is noticeable but small compared to that from boost-phase defenses.

Midcourse penetration scales as $\approx \exp(-I/M_s)$. For K = 2,000, or I = 500 interceptors, there are from Figs. 5 and 6 $\approx$ 150 ICBM plus 500 SLBM RVs penetrating to midcourse, which gives $\exp(-500/650) \approx 45\%$ penetration, or $0.45 \cdot 650 \approx 300$ RVs on target, as seen on Fig. 7 at 2,000 SBIs. Even with 600 ICBM and 3,200 SLBM RVs surviving prime's first strike, only a few hundred RVs penetrate to retaliate. By 4,000 SBIs less than a hundred RVs penetrate. The contribution from ICBMs and SLBMs is an order of magnitude less than that expected from bombers and cruise missiles; it could essentially be dropped.

C. Total Strikes

At large K the bulk of the retaliation is carried by that from the bombers shown on Fig. 4. Their main advantage is the assumption that they can be preempted, but that once airborne, they are invulnerable to the boost and midcourse defenses which attrit RVs so strongly. Bombers are added to the residual missile RV restrike against value, R_{2p}, from Fig. 7, to give the total restrike

$$R_2 = R_{2p} + a \cdot p \cdot b \cdot B_s, \qquad (8)$$

where a, p, and b are unprime bomber alert rate, penetration probability, and weapons per base, respectively.

Figure 8 gives $\delta V_{1m}'$, the number of value targets destroyed by prime's penetrating RVs. The top curve is for midcourse defenses only; the middle curve for boost only; and the bottom curve for both. All are calculated under the assumption that the value targets are defended preferentially by the rest of the interceptors against the residual threat.

For K small essentially all value targets are killed because of the enormous influx of ICBM and SLBM RVs and airborne weapons. By 1,000 SBIs only about 750 targets are, due partly to attrition of the threat by the increased number of boost-phase SBIs and partly to the increasing number of preferential midcourse interceptors faced. For combined defenses, by 2,000 SBIs the value strikes fall to 250; by 3,000 to zero. In reducing strikes on value, a combination of boost and midcourse defenses is significantly more effective than either alone. By the point at 3,000 SBIs where $\delta V_{1m}' \rightarrow 0$, prime's objective of suppressing unprime's value is completely denied, and that component of his first strike cost rises to L' even without the bombers' contribution.

Prime's total strike on unprime's value is the sum of his missile strike and his essentially unattritted aircraft strike, which totals to

$$R_1' = \delta V_{1m}' + a'p'b'B' \qquad (9)$$

weapons. Since $\delta V_{1m}'$ falls sharply beyond ≈ 2,000 SBIs, for significant defenses the strike is essentially $R_1' \approx a'p'b'B'$. Ideally, the attacker could alert all aircraft to achieve $a' \approx 1$ to maximize aircraft survivability, but doing so could alert unprime and lose the benefit of striking first. Thus, some $a' < 1$, possibly not much greater than the normal alert level, would be used instead.

The penetration p' should be high against suppressed defenses, but Figs. 1 and 2 show that against strong defenses there might not be enough penetrating RVs to spare for their suppression. In that case p' could fall significantly from the 0.6 used as a basis. That variation is studied elsewhere, but it can be noted in passing that if both ICBM and SLBM RVs can be used to suppress bomber defenses, and p' has the simple functional form

$$p' \approx 1-\exp\{-[R_{1m}'+R_{1n}']/[R_{1m}'+R_{1m}'(K=0)]\}, \qquad (10)$$

then for K = 0, $p' = 1-e^{-1} \approx 0.63$, the nominal value used above, and from Figs. 1 and 2 the drop in $R_{1m}'+R_{1n}'$ from 0 to 2,000 SBIs is from 5,000 to 1,200, so $p' \approx 1-\exp(-1,200/5,000) \approx 0.21$, about a factor of 3 drop, which would produce a like decrease in the bombers' contribution. For K = 4,000 SBIs p' ≈ 1-exp(-500/5,000) ≈ 10%, a factor of 6 reduction in each.

These estimates assume that the fraction of the surviving RVs is kept constant. For strong attrition it can be argued that fewer RVs could be diverted to bomber defense suppression. It can also be argued that all should be diverted. Given the modest contribution from RVs to the strike then, it would appear that the latter would be the more effective allocation, but there would still be a drop in penetration.

Figure 9 shows the number of strikes on value as a function of K for boost-phase only defenses. The top curve is R_2 from Eq. (8). At K = 0 it is ≈ 4,000 RVs, consisting largely of the unattritted SLBM RVs of Fig. 6 and the bomber weapons corresponding to Fig. 4. By 2,000 SBIs the former are largely eliminated, and R_2 falls to the ≈ 1,000 weapons from bombers.

The next pair of curves are R_1 from Eq. (9) and R_1' from its conjugate, which are similar because of the symmetry of first strike forces under START. They, too, are largely made up of SLBMs at small K and bombers at large K. R_2 is larger than R_1 at small K because unprime's first strike is distributed over missiles, bombers, and value, while R_2 is concentrated on value, the only remaining target. The bottom curve is R_2', prime's retaliation. It starts ≈ 1,000 RVs below R_2 because under START prime has fewer SLBMs and more ICBMs than unprime, and ICBMs are more heavily suppressed than SLBMs by unprime's first strike. By 2,000 SBIs, R_2' also falls to just the strikes from bombers.

Figure 10 shows the number of strikes on value as a function of K for both boost-phase and midcourse defenses. The middle pair of curves, R_1 and R_1', are little changed from Fig. 9. The top and bottom curves, R_2 and R_2', are also little changed for K < 1,000 SBIs, but at that point they reach a minimum, turn upward, and reach ≈ 2,000 RVs by 4,000 SBIs.

The reversal is due to the important contribution from bombers at large K and from Fig. 4's demonstration that large defenses can increase the number of bombers surviving by about a factor of 3. This reversal makes the ratio of second to first strike weapons for large K about 2 in Fig. 10 versus 1.3 in Fig. 9. That increase in the ratio of second to first strikes suggests intuitively that combined boost-phase and midcourse defenses are more stable than boost-phase defenses, an impression that is explored quantitatively below.

D. Costs

Figure 11 shows the costs from Eqs. (3), (4), and their conjugates as functions of K for boost-phase defenses only. The top cost, C_2, is relatively flat, dropping gradually to ≈ 0.8. C_1 starts at about the same value, falls sharply until $K \approx 2{,}000$, and then stabilizes at about 0.6. C_2' starts lower at ≈ 0.8, falls, and then stabilizes at about the same level. C_1' falls throughout from an initial ≈ 0.9 to ≈ 0.5. This is almost a factor of two drop in prime's first strike costs, which causes a significant erosion in prime and overall stability indices. It particularly indicates a loss of deterrence of prime, who looks to the ratio C_1'/C_2' to evaluate any possible advantage from striking first, and that ratio would fall from 1.1 to ≈ 0.77.

Figure 12 shows the costs for combined boost-phase and midcourse defenses. C_1 and C_1' again fall initially, but at about 1,500 SBIs they turn upward and reach values even higher than their values at $K = 0$. The reversal is again because of the penetrating contributions from the additional protected bombers shown in Fig. 10. C_2 and C_2' fall, roughly in proportion, to about 0.5-0.6. That also indicates an improvement, as the costs for striking only in retaliation fall about a factor of 2 overall. For large K the ratios in costs, like those in strikes, again approach $C_1'/C_2' \approx C_1/C_2 \approx 2$.

E. Stability Indices

Figure 13 shows the stability ratios or indices as a function of K for boost-phase defenses only. The individual indices C_1'/C_2' for prime and C_1/C_2 for unprime start at 1.1 and 1, respectively, at $K = 0$, as does their product, the composite index Q. By 2,000 SBIs, however, both sides' indices have fallen to about 0.8, and the composite to about $0.8^2 \approx 0.6$. The drop in the composite comes largely from the roughly equal drops in C_1 and C_1' on Fig. 11. They in turn come from the 4- to 5-fold drops in R_2 and R_2' in Fig. 9, which are due to the uncompensated draw-down of SLBMs and ICBMs by boost and midcourse defenses.

Figure 14 shows the composite stability indices for boost-phase defenses, midcourse defenses, and combined boost-phase and midcourse defenses. The bottom curve, also the bottom curve of Fig. 13 for boost-phase defenses only, drops monotonically with K for the reasons discussed above. The curve for midcourse defenses is relatively flat for reasons explored below. The curve for combined boost-phase and midcourse defenses first drops slightly, reaches a minimum of about 0.8 at about 1,000 SBIs, and then climbs sharply to ≈ 3.3 at 4,000 SBIs.

The reason for the climb is once again the increase in C_1 and C_1' and strong decrease in C_2 and C_2' in Fig. 12, which are due largely to the ≈ 4-fold increase in R_2 and R_2' in Fig. 10 due to the enhancement of the survivability of bombers in Fig. 4. The overall impact is significant. Boost-phase-only defenses appear strongly destabilizing; midcourse defenses are essentially neutral. Combined boost and midcourse defenses, however, apart from a small transient as modest defenses draw down land- and sea-based missiles, increase stability indices significantly. The fundamental reason for the difference between the three curves is the strong impact of midcourse interceptors and their preferential operation, particularly in conjunction with useful levels of boost-phase attrition, in enhancing the delayed, essential contribution from bombers and cruise missiles.

VI. MIDCOURSE DEFENSES AND DECOYS

Given the reduced variances of strikes, costs, and stability indices of midcourse-only defenses relative to those of boost-phase-only defenses it is worthwhile exploring how that insensitivity comes about. That exploration also gives a quick insight into the impact of decoys on midcourse defenses.

A. Midcourse Defenses

The basic mechanism that makes midcourse-only defenses effective and stabilizing is exhibited in Figs. 3 and 4: midcourse defenses are preferential and hence can concentrate on and defend some fraction of the retaliatory forces, no matter how large the threat. That is the same leverage discussed earlier for limited defenses of Minuteman or MX missiles.[10] The one additional point is that if both sides used only midcourse defenses, the surviving forces would exhibit little attrition during restrike, as shown in Fig. 7, so the lesser number of survivors would be just as effective a deterrent. The earlier figures only show that scaling to 1,000 interceptors; those below carry it further.

Figure 15 shows the components of unprime's restrike as functions of I. For I small, the first curve from the top is the total restrike R_2; the next is the SLBM component R_{2n}; the next is the total number of penetrating RVs, R_{2p}; the next is the surviving bomber weapons, W_b; and the bottom is the surviving ICBM RVs, R_{2m}. The ICBM RVs start at zero for I = 0 but grow steadily, reaching the ≈ 250 of Fig. 5 by 1,000 GBIs, 800 by 4,000 GBIs, and 1,200, or ≈ 80%, of the ICBMs by 8,000. The bombers are just above and parallel to the missiles, because both are protected preferentially. The bombers amount to about half of the restrike by 4,000 GBIs. The SLBM contribution R_{2n}, the line above, is straight since SLBMs are not attacked and have no boost phase to penetrate.

The penetrating RVs start out at just the number of SLBMs. Although the input to midcourse, R_{2p}, increases with the ICBM RVs saved by I, the number penetrating decreases due to the faster increase in I. The RV contribution falls to 1,500 at 4,000 and to 750 at 8,000 GBIs. The total restrike R_2 falls to about 3,600 RVs at 1,000 GBIs, 3,100 at 4,000, and 2,800 RVs at 8,000 GBIs, where over 70% are from bombers.

Figure 16 shows the resulting strikes on value for both sides. The top curve is R_2 from Fig. 15. The next is R_2'.

Figure 15 shows that the restrike is made up of protected ICBM RVs plus SLBM RVs. Prime has fewer SLBMs, so the increase in ICBMs is more significant, and the sum adds to almost constant penetration. By 4,000-8,000 GBIs R_2 and R_2' differ only 20-30%. The curves for R_1 and R_1' are almost the same, reflecting comparable heavy ICBM RVs and midcourse defenses that are only sensitive to RVs, not missile basing or deployment speed. They become flat at 5,000 GBIs, where all value targets are protected, and the attacker's value objective is completely negated.

Figure 17 shows the costs. The top two are for C_1 and C_1'; the bottom two for C_2 and C_2'. The first rise slightly; the bottom fall strongly until all value targets are exhausted. Thus, in Fig. 18 the stability indices rise monotonically and sharply until about 5,000 GBIs, where the composite index reaches about 4.5. Again, the dominant contributions are the lowering of the cost of retaliation by protecting more missiles and allowing the survivors to penetrate fewer defenses.

It should, however, be noted that the levels of surviving, penetrating retaliatory forces are high. At 4,000 GBIs they would be about 3,000 weapons, as opposed to the 600-800 for 4,000 boost-phase SBIs or 1,500-2,000 for boost and midcourse. Midcourse defenses protect rather than remove retaliatory weapons. Of course all of the retaliatory bursts would be over the initiator's territory, and for 4,000 GBIs, 50% or more of them would be on recallable, manageable bombers.

B. Decoys

These results provide a preliminary insight into the impact of the numerous light decoys that could be used to dilute the effectiveness of midcourse sensors. The number is a competition between the ability of the offense to generate light decoys and that of the defense to discriminate them.[11] If it results in D undiscriminated decoys per RV, the impact on the midcourse defense is to divide the number of interceptors by 1 + D, i.e., the RV plus D decoys. The actual number of decoys might be much larger. If there were 20 decoys per RV, which is feasible, and

80% of them were discriminated, there would only be D = 4 per RV left. In the near term discrimination might not be that good. If only 40% were discriminated, that would leave 12.

The previous figures can be used to assess the impact of decoys. For D = 4 decoys per RV, Fig. 15 should be entered at the abscissa at an effective number of I/5 GBIs. Thus, if the defense had 5,000 GBIs, the effective number would be 5,000/5 = 1,000. From Fig. 16, R_2 would then be 3,600 rather than 3,000, and from Fig. 18, the composite stability index would be 1.3 rather than the 4.7 without decoys.

The defense could restore performance and stability by buying D times more GBIs, but that could be expensive and might not be feasible in the near term.[12] Of greater concern, however, is the impact of decoys on the stability index of combined boost and midcourse defenses. It is obvious from the dip near 1,000 GBIs in Fig. 14 that the midcourse increases the stability index from what would obtain from boost phase alone, and that saturating the midcourse with decoys would collapse the combined stability curve down onto the boost phase only. The impact of intermediate levels of decoys on the index requires study; it cannot, however, be attempted here.

C. Sensitivities

In addition to the primary sensitivities of strikes, costs, and stability indices to the number of boost and midcourse interceptors discussed above, there are lesser sensitivities to the details of attack and defense allocation over missiles, bombers, and value and to the details of the target set that are worth mentioning but not large enough to require that they be treated in the text.

Attack allocation is an interesting example. Given the complexity of the equations in Appendix A and the hard limiting of the defenses, one might expect that there would be strong sensitivities to the allocation of attacks and defenses. There are not. Appendix D and Figs. 19-22 show that their optimization for strategic forces in which bombers are discounted on the attack and fixed in the restrike involves shallow and quite broad minima. Appendix E and Figs. 23-26 show that the more complicated optimizations when the bombers are treated interactively produce, if anything, weaker minima. For both, the penalties in strikes, costs, and indices for operating well away from the minima are quite small. Minimizing restrikes reduces them slightly, but the impact on stability is slight compared to the primary sensitivities to defenses. Hence, the rough partitions used in the calculations above produce overall indices that are changed little by wide variations in allocations.

Sensitivity to the target set used is somewhat greater, and somewhat confusing. Fig. 26 shows the stability index for a calculation with 2,000 boost-phase interceptors only. The abscissa is the number of value targets held at risk. For the calculations above those numbers are 2,000 and 4,000 targets. The figure shows the effect of varying those numbers, which is done by varying k and k', since k is essentially 2 over the number of targets.

For this nominal interaction, 2,000 targets is a break point. Larger values do not shift the indices significantly, but smaller numbers do. At 2,000 SBIs the composite index is about 0.68; by 500 targets all three rise to ≈ 1. Thus, the degree of stability or instability predicted varies with the number of targets held at risk. That follows simply from the observation that for a given R, as the number of targets decreases, or k increases, $\exp(-kR)$ increases, which reduces damage limiting costs and increases value costs as noted below Eq. (6).

The point has little impact on the START forces used above, but if the strikes and restrikes are directed to much smaller target sets, in the limit $C_1/C_2 \rightarrow 1/1$ as seen above. Conversely for large sets, small k, $C_1/C_2 \approx (kR + L)/(k'R + L')$, which for $k \approx k'$ and $L \approx L'$ tends to unity as seen in Figure 26. The point is not academic. The targets to include or exclude are not fixed; some discretion is involved. Those who have a vested interest in seeing instability could increase the target set. According to Fig. 26, a large set works against the stability evaluation of boost phase defenses. Were the sets smaller they could look acceptable by themselves.

Again the point is not pivotal for START, but for follow on reductions the sensitivity could play more directly. Overall, the strikes and restrikes, R, do vary with the initial force levels. Thus, if force levels were reduced without reducing the target sets as well, the kR products would fall and the stability indices would degrade because of the lesser satisfaction of value objectives, even though fewer weapons could fall on either country.

This means that to maintain an index of stability that is independent of the target list it would be necessary to reduce the desired target set as the strategic forces fell or to negotiate away the value targets proportionally as strategic forces were reduced. Otherwise, one would be in a situation in which the logical, and accepted, formalism for evaluating stability indices would automatically indicate that smaller offensive deployments were less stable and larger ones more so.

VII. CONCLUSIONS

This note presents calculations of two-sided strategic interactions and interprets them in terms of stability criteria for various offensive and defensive force combinations. According to them the current offensive deterrence configuration is quite stable. The issue is the extent to which stability indices are shifted by the deployment of varying numbers of boost or midcourse defenses.

The currency for cost is damage to self and other; the objective is to prevent the former and retain the capability for the latter. The index does not determine whether or not either side would strike, which depends on other factors, but it does reduce the results of complicated calculations into a single index consistent with U.S. and Soviet estimates of correlations of forces. Both sides need to see the situation from the other's perspective; each should be able to see and willing to play the game from either side, which the formalism used reinforces.

For moderate boost-phase layers, ICBMs play little role in first strikes, let alone second; heavy ICBMs play none. SLBMs are attritted harder even when clustered before launch; they contribute only against small boost-phase defenses. The larger numbers of surviving missiles launched with defenses helps penetration, but the larger number of boost-phase defenses they encounter offsets it. Even with a large fraction of ICBMs and SLBMs surviving the first strike, only a few penetrate to retaliate. For large defenses the contribution from ICBMs and SLBMs is an order of magnitude less than that expected from bombers and cruise missiles.

Today the brunt of retaliation is carried by ICBMs, SLBMs, and bombers. With strong defenses the contributions from ICBMs and SLBMs would largely be suppressed, and the main role of defenses would be to increase the survivability of the bombers and cruise missiles, which would deliver the bulk of the restrike. Stability indices would then not be changed greatly if the ICBMs and SLBMs were deleted and the midcourse defenses used to defend the bombers.

Boost-phase defenses are unable to attrit missile attacks enough to save significant numbers of undefended fixed targets. Overall attrition is adequate, but without preferentiality they cannot usefully convert attrition into targets saved, which undermines their contribution to stability. Midcourse layers could at all levels protect a significant fraction of ICBMs due to their preferential operation. Combined boost and midcourse defenses could defend a large fraction.

Without defenses, bomber restrikes are critically dependent on alert rates; with defenses that strong sensitivity is largely removed. Defending bombers is a key interaction for promoting stability, which boost and midcourse defenses should be able to perform as well for bases as for missile silos.

Combined defenses give increasing stability indices due to the important contribution from bombers and the fact that large defenses can significantly increase the number of surviving bombers. That increases the ratio of second to first strike costs, which makes the stability indices of combined defenses much greater than those for boost-phase-only defenses. Overall, boost-phase defenses appear destabilizing; and midcourse defenses appear neutral; but combined defenses increase stability indices significantly. The fundamental difference between the three is the preferential impact of midcourse interceptors, particularly in conjunction with useful levels of boost-phase attrition, in enhancing the contributions from bombers and cruise missiles.

Relevant numbers of decoys could reduce composite stability indices by large factors. Saturating midcourse defenses with decoys would collapse the combined stability curve down onto that of the boost phase only. Studies of attack and defense allocations indicate modest penalties for non-optimal choices. Sensitivity to the target sets used is greater. If force levels were reduced without reducing the target sets, stability indices would appear to degrade just because value objectives were reduced, even though fewer weapons could fall on either country. For the indices to be independent of target set it is necessary to reduce the value targets along with strategic forces or to negotiate away targets in proportion to strategic forces as they are reduced. Otherwise the accepted formalism automatically indicates that smaller offensive deployments were less stable and larger ones were more stable just due to the scaling nature of the damage curves.

This paper has discussed only a few of the sensitivities of this stability model. On the basis of the results it appears that the issues most needing further work are the impact of decoys on combined defenses and the possibility of a parallel build down of offensive forces and build up of defenses in cooperative or independent deployments.

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APPENDIX A. EXCHANGE MODEL

The model used is an extension of one developed earlier for midcourse defenses,[13] but boost-phase and midcourse defenses are added explicitly. Terminal defenses are not, since they would contribute little attrition to that from the first two layers for the current concepts. The two sides are identified only as prime and unprime, referring to their symbols in the model's equations, although the forces for unprime in Appendix B correspond roughly to those of the U.S. and those for prime roughly to those of the Soviet Union under START constraints. From the overall view of crisis stability one is concerned that configurations appear stable from both sides. The prime-unprime notation helps to keep that perspective paramount.

A. Offensive Forces

The offensive forces treated are land based intercontinental ballistic missiles (ICBMs), submarine launched ballistic missiles (SLBMs), and aircraft (bombers, cruise missiles, and carriers). Unprime's forces in those categories are denoted by M, N, and B, respectively; prime's by M', N', and B', respectively. Unprime's boost and midcourse defensive forces are denoted by K and I, and prime's by K' and I', respectively.

B. Defensive Forces

Midcourse defenses are treated as preferential, which is in accord with the characteristics of current ground-based interceptors (GBIs) and their sensors. Adaptation could improve their performance 20-30% at modest threat levels; its advantage saturates at the larger threats involved in stability analyses.[14]

Boost phase defenses are treated as non-preferential, in accord with the operation of current space based interceptors (SBIs) and their sensors.[15] The SBIs are, however, given credit for being able to work singly or in concert to provide efficient shoot-look-shoot defenses without disproportionate increases in constellation sizes. SBI availability is estimated from a geometrical model corrected for optimized orbits,[16] which compares closely in availability with exact solutions.[17] The variation of the number of RVs killed per SBI with constellation size is treated through a fit to the exact solutions; the corrections are significant for the modest constellations considered here.[18]

Decoys are treated parametrically. It can be argued that they might not be deployed in numbers in the near term, and that in the midterm when they were deployed in numbers, capable discrimination should be available.[19] Their impact on the midcourse layer, whose performance is essential for stability, is so great that provision is made for some number of decoys per reentry vehicle (RV).

C. First Strike

If prime strikes first the number of RVs he could deliver on unprime in the absence of defenses would be $m'M' + n'N' + a'p'B'$, where m' is the number of RVs per prime ICBM, n' the number of RVs per SLBM, and a' and p' are prime aircrafts' alert rate and probability of penetration, respectively. If unprime deploys boost phase defenses, they would decrease the number of ICBMs by approximately $f \cdot K$, where f is the fraction of unprime's SBIs able to reach prime's ICBM launch area. f is essentially the ratio of the area in the SBIs' constellation from which they are kinematically capable of reaching prime's launch area to the whole area over which the constellation is distributed.

In the near term for current forces and dispositions, $f \approx 0.2$. With START-limited forces in heavy missile deployments, f could drop to 0.1-0.13. For $fK > M'$ there would be more SBIs available than missiles launched; essentially all of prime's ICBMs would be destroyed. Thus, the ICBM contribution to prime's first strike is approximately $R_{1m}' = m'(M' - fK)$ for $f'K' < M$, and 0 otherwise.

This approximation properly estimates the number of SBIs needed to intercept each missile, but it ignores the reduction in the number of RVs left on its bus as more RVs are deployed with the passage of time. That effect is calculated elsewhere.[20] The exact results are not needed. For the accuracy of the estimates pursued here it is permissible to use a simple exponential fit

$$R_{1m}' = m'M'\exp(-fK/M'), \quad \text{(A1)}$$

which agrees with the exact solution for fK small, vanishes rapidly for $fK > M'$, and is close to the exact solution overall. The predicted number of RVs killed is close to the exact result overall, and is within about 10% of it near $K \approx M'/f$, where the approximation is worst.[21] The error in the number of penetrating RVs is larger; it is comparable to the uncertainties in the SBIs' kill probability, predicting too much penetration.

For typical near-term parameters, $fK \approx f_nK \approx 0.1 \cdot 4{,}000 \approx 400$, so that for a START-limited heavy missile $M' \approx 250$, the exponential in the first term is $\approx e^{-fK/M'} \approx e^{-400/250} \approx 0.2$. Thus, the heavy missiles are attritted but not eliminated.

The fraction of defenders available can be quite different for SLBMs than for ICBMs, since an isolated submarine essentially represents a point launch, for which SBIs scaled for ICBMs are oversized. An exponential approximation to their penetration is

$$R_{1n}' = n'N'\exp(-f_nK/N_b'), \quad \text{(A2)}$$

where f_n is the availability of unprime boost phase defenders over prime's submarine launch areas and N_b' is the effective number of SLBMs per submarine.

For the launch of all of a submarine's ≈ 16 SLBMs against a constellation of $K \approx 4{,}000$ SBIs, the exponential is $\approx e^{-400/16} \approx 10^{-11}$, so that none would survive. Even for clustered launches from ≈ 5 submarines in port or bastion the factor would be $\approx e^{-400/80} \approx 1\%$, so few would penetrate. Boost-phase defenses fall disproportionately hard on SLBMs, essentially eliminating their contribution to first strikes or retaliation.[22]

Thus, in assessing SLBMs' impact it is assumed that the submarines in port and bastions are clustered, and moreover that those on patrol rendezvous within a few hundred kilometers of each other before launch to improve penetration. In that case there is one cluster at sea and one in port for each ocean, or a total of four point launches, each with approximately N'/4 SLBMs. In that case the penetration probability for each is approximately $\exp[-fK/(N'/4)]$, so that $N_b' \approx N/4$, and the total number of penetrating SLBM RVs would be

$$R_{1n}' \approx n'N'\exp[-f_nK/(N'/4)]. \qquad (A3)$$

The exponent is reduced from that for the penetration probability of a single submarine by a factor of $(4/N')(1/16) \approx 4\cdot16/20\cdot16 = 1/5$, which is the difference between some penetration and none. Submarines do not now rendezvous at sea, so this procedure obviously overestimates their contribution. However, once boost-phase defenses are deployed they would have to plan to do so or their contribution would largely be discarded.

With this approximation for SLBMs, the number of penetrating RVs in the midcourse threat is the sum of R_{1m}' and R_{1n}', or

$$R' = R_{1m}' + R_{1n}' = m'M'\exp(-fK/M') + n'N'\exp(-4f_nK/N'). \qquad (A4)$$

These penetrating RVs can be used on unprime's missiles, bombers, or value. Optimal allocations are discussed in Appendix D. Here it is simply assumed parametrically that a fraction x is allocated to missiles, a fraction y to bombers, and the remaining 1-x-y to value targets.

If prime struck all of unprime's M missiles with $x\cdot R_{1p}'$ RVs, that would give an average of xR_{1p}'/M RVs per missile. By committing a like number of interceptors to it, any given missile could be saved. Thus, with I interceptors, of which gI were allocated to missiles, unprime could save

$$M_s \approx gI/(xR'/M) = M(gI/xR') \approx M[1-\exp(-gI/xR')] \qquad (A5)$$

missiles. This expression is of the same form as that for the boost phase, is exact for $I << xR'/g$, and rises to M for $I >> xR'/g$. For $I \approx 1{,}000$ GBIs and roughly equal fractions of the attack and defense allocated to missiles, $gI/xR' \approx 1{,}000/R'$, so if boost-phase penetration is high so that $R' > 1{,}000$ RVs, i.e. about half the ICBMs penetrate, then M_s/M is proportional to I/R', which is small, so that unprime's ICBMs contribute little to retaliation. Thus, the condition for suppression of missiles is essentially $xR'>gI$.

If unprime's bomber bases can be protected preferentially, the number of surviving retaliatory weapons on bombers is

$$W_{2b} = \{a + (1-a)[1-\exp(-hI/yR')]\}\cdot bB, \qquad (A6)$$

where the first term represents the bombers on alert that escaped and the second those that were defended successfully. The attacker cannot control the former; the criteria for him to suppress the latter is $yR' >> hI$. This can generally be accomplished, but only at the expense of removing defense from missiles or value.

The damage to unprime value is the residual portion of the penetrating RV force, or

$$\delta V_{1m}' = V\{1 - \exp[-(1-g-h)I/(1-x-y)R']\}, \tag{A7}$$

up to a maximum of $(1-x-y)R'$ targets, the number of RVs committed to value, where by Eq. (2) $V = 1.9/k$. $\delta V_{1m}'$ does not contribute to unprime's restrike but does contribute to his ability to maintain control, recover, and defend.

Prime's bombers arrive later, when surviving missiles and bombers have been launched. Thus, the bombers' targets are unprime's value. Assuming that aircraft are not susceptible to the missile defenses once in flight and that their penetration is characterized by a probability p', prime aircrafts' damage to value is $W_{1b}'p'a'b'B'$, and prime's total damage to unprime value

$$R_1' = \delta V_{1m}' + p'a'b'B'. \tag{A8}$$

Ideally, the attacker would alert all aircraft to achieve $a' \approx 1$ to maximize aircraft survivability and contribution to $\delta V_{1m}'$, but doing so could alert unprime, degrade surprise, and lose the benefit of striking first. Thus, some value $a' < 1$, possibly not much greater than the normal level, would be used instead. Other planes might get off and contribute, but that is not assumed here other than parametrically through a'.

D. Second Strike

Prime's first strike having been completed, unprime's second strike is constituted from unprime's surviving missiles, bombers, and SLBMs. Equation (A5) gives the surviving missiles. The RVs penetrating prime's boost-phase defenses are given by

$$\begin{aligned} R_{2m} &= mM_s\exp(-f'K'/M_s) \\ &= mM\cdot\exp(-f'K'/M_s)[1-\exp(-gI/xR')]. \end{aligned} \tag{A9}$$

The number of surviving SLBM RVs is

$$R_{2n} = nN \cdot \exp(-4f_n'K'/N), \tag{A10}$$

which is reduced relative to R_{2m} by the fact that 4/N is generally larger than $1/M_s$, but is increased by the fact that $M[1-\exp(-gI/xR')]$ is generally much smaller than N. The sum of R_{2m} and R_{2n} form the penetrating missile restrike $R_{2p} = R_{2m} + R_{2n}$, which is further attrited by prime's midcourse defenses to

$$R_{2p} = (R_{2m}+R_{2n})\exp[-I'/(R_{2m}+R_{2n})]. \tag{A11}$$

These penetrating RVs, together with the W_{2b} air-borne weapons from Eq. (A6), are all directed to prime's value, since his missiles and bombers having been expended. They give a restrike

$$R_2 = R_{2p} + W_{2b} \tag{A12}$$

in retaliation. At that point the first and second strikes are complete.

The discussion above has assumed that prime struck first and unprime retaliated second. To obtain the equations for unprime striking first it is only necessary to conjugate Eqs. (A1)-(A12). Alternatively, it is possible to use the same equations for both and interchange the parameters describing prime and unprime's offensive and defensive forces.

E. Costs

From the conjugate of Eq. (3), the cost to prime for striking first is

$$C_1' = 1 - \exp(-k'R_2) + L' \cdot \exp(-kR_1'), \tag{A13}$$

where from Eq. (A12) $R_2 = R_{2p} + W_{2b}$, and from Eq. (A8), $R_1' = \delta V_1' = \delta V_{m1}' + p'a'b'B'$. Then from the conjugate of Eq. (4),

$$C_2 = 1 - \exp(-k \cdot R_1') + L \cdot \exp(-k'R_2). \tag{A14}$$

with the same R_1' and R_2. The equations for C_1 and C_2' are their conjugates. In them R_1 and R_2' are obtained from the conjugates of Eqs. (A1)-(A12). Typical results are given in the text.

APPENDIX B. OFFENSIVE FORCES

Basic calculations assume START-limited offensive forces. While there are remaining uncertainties, Soviet strategic offensive forces are relatively well defined. The calculations below use 154 heavy silo-based SS-18 or follow-on missiles and 112 SS-24 rail-mobile SS-24s, each with 10 reentry vehicles (RVs), plus 344 road-mobile, single RV SS-25s. That gives a total of 610 land-based missiles and 3,004 RVs, all of which are assumed to be on line.

They also assume 324 submarine launched ballistic missiles (SLBMs) with an average of 6 RVs per launcher for another 1,896 RVs; 86% of which are assumed to be on line.[23] There are a total of 275 bombers and cruise missile carriers with 4,100 actual weapons, about 85% of which are on line. They are assumed to be dispersed over about 20 bases with an alert rate of ≈ 30%.

Fixed ICBMs are assumed to be deployed in the ≈ 1,000 km diameter area in which current heavy missiles are deployed. The deployments of mobile ICBMs and SLBMs are varied. Heavy missiles are taken to have the roughly 300 second booster burn time and 300 second deployment times of current SS-18s. Variations for SS-24s and SLBMs do not impact the calculations below. SS-25s are taken to have 300 s burn and 30 s deployment times.

U.S. forces are taken to have 816 missiles with a total of 3,264 weapons, most on line. That mix is assumed to have about 750 Minutemen and about 50 MX rail mobile missiles. Since all have comparable burn plus deployment times and the number of mobiles is small, they are not differentiated. A total of 408 SLBMs with about 6 RVs each for a total of 4,700 RVs are assumed to be distributed over about 20 submarines. The 376 bombers and cruise missile carriers are assumed to carry 4,672 weapons. All bombers are assumed to be capable of penetrating the suppressed defenses they would face in cases of interest. The bombers are assumed to be distributed over about 20 airfields with a base alert rate of 30%.

APPENDIX C. DEFENSIVE FORCES

SBIs are assumed to have a total velocity increment $V \approx 6$ km/s. Thus, in engaging missiles with a total burn plus deployment time T, the SBIs can reach them from a distance $W + V \cdot T$ from the center of a launch area of effective radius W. The mapping that minimizes the number of SBIs required for uniform coverage uses the SBIs nearest the center on missiles near the center of the launch area and those near Y on missiles near W.[24]

The fraction of the K SBIs in the constellation within range of the launch is

$$f = z\pi(W+VT)^2/4\pi R_e^2, \qquad (C1)$$

where $R_e \approx 6{,}400$ km is the earth's radius, and $z \approx 2.5/\sqrt{(W+VT)}$ is a factor[25] that represents the constellation concentration possible over launch areas of modest latitudinal extent.[26] The integral of the influx of SBIs into the launch corridor gives the total number of missile kills. Up to time T it is[27]

$$M_K = zK[(W+VT)/2R_e]^2. \qquad (C2)$$

For the SBIs to engage each missile or bus at least once by T requires $M_K = M$. For larger constellations all of the missiles could be engaged once by

$$T_1 = [2R_e\sqrt{(M/zK)}-W]/V, \qquad (C3)$$

so that for heavy missiles and typical constellations the number of RVs killed is

$$R = [W^2 + 3WVT_1/2 + 7V^2T_1{}^2/12]m_o pzK/4R_e{}^2, \qquad (C4)$$

Eqs. (B3) and (B4) are essentially exact, but awkward to use in the overall model, so the exponential approximations discussed in Appendix A are used instead. They approximate Eq. (C4) well except near $fK \approx M$.[28]

Current launch areas have $W \approx 1{,}800$ km, and current heavy missiles have $T \approx 600$ s, so $z \approx 1.1$, and $f \approx 0.20$, i.e., about 20% of the SBIs could reach current distributed launches. If the missiles were rebased into the $W \approx 500$ km of current heavy missiles, f would decrease about 35% to $f \approx 0.13$.

Heavy mobiles can be concentrated before launch somewhere in the area, but given their long burn and deployment times the impact is not great. For 600 s and $W = 0$, the fraction available would be slightly over 10% if the SBIs were inclined for the mobiles, and slightly under 10% if they remained optimized for the fixed missiles. Weighted according to RVs all heavy missiles would have an average availability of 20% for current basing and 11-12% for rebasing in a 1,000 km diameter area.

Submarines have $W \approx 0$, for which $f \approx 0.10$, although that only partly characterizes their attrition. If they are concentrated in 4 points before launch to enhance penetration, that gives about 100 SLBMs per site. Thus, compared to the launch of 800 missiles with $f \approx 0.2$, the SLBMs would experience attrition greater by a factor of $e^{-0.2 \cdot 4,000/800}/e^{-0.1 \cdot 4,000/100} \approx e^{3} \approx 20$. For the Soviet Union with 260 heavy missiles, the difference would only be a factor of $e^{1} \approx 3$. Both are attritted strongly.

Fast, singlet missiles with $T \approx 300$ s from point launches have $f \approx 0.04$, if launched by themselves, or ≈ 0.03, if launched with the heavy missiles. That would make them much more difficult to intercept, although they would carry relatively few RVs. The issue is studied in some detail elsewhere, but the main results can be simply illustrated.[29] If all 4,000 SBIs were allocated to them, singlets would be attritted $\approx e^{-0.04 \cdot 4,000/344} \approx 0.63$, or about 30%. If, however, the SBIs were allocated to the missiles on the basis of their RV content, only about 10% would go to the singlets and they would only be attritted by a factor of $\approx e^{-0.03 \cdot 400/344} \approx 0.97$, or about 3%.

Singlets would be addressed strongly only by much larger constellations than those treated here. Thus, the calculations in the text assume that they are not attritted at all in boost phase. Instead, heavy missiles are attritted with the $f \approx$ 10-20% estimated above, and the singlet RVs are added directly to the penetrating RVs of Eq. (A1).

APPENDIX D. DAMAGE LIMITING VERSUS COUNTER VALUE TARGETING

A given number of penetrating RVs in a first strike can either be directed towards retaliatory forces in order to limit the damage the attacker would receive in return, or towards value in order to limit the opponent's ability to project force through other means and in other theaters. The proper allocation of forces between those two tasks is isolated and examined here within the framework discussed in the text. This section treats the allocation of attacks and defenses for forces in which offensive bombers are omitted and the defenses of restrike bombers are fixed. That restriction is removed in the next appendix.

The missile first strike is characterized by the number of penetrating RVs. Bombers arrive later and are assumed to strike value targets unopposed. Submarine-launched missiles are assumed invulnerable before launch. Hence they are not included here because they do not impact and are not impacted by the damage limiting versus value targeting decision. Retaliatory forces are lumped together and measured by total weapons, since it can be shown that if the goal is simply suppression of the restrike forces, the optimal targeting for a combination of missiles, targetable aircraft, and value targets is simply to both strike and protect them in proportion to the number of warheads they represent.

The midcourse defense consists of I interceptors, used preferentially. Prime is assumed to direct a fraction x of the R penetrating RVs at retaliatory missiles and a fraction 1-x of them at value targets. Thus, a fraction $I/R < 1$ of the missiles could be defended. If they faced an equal number of prime defenders and interceptors in transit, the restrike would be

$$R_2 \approx \max\ [mM \cdot \min(I/xR,1)) - I',\ 0] + B, \qquad \text{(D1)}$$

where the limits just keep the defenses from driving the second strike below zero, in this approximation, or impacting the airbreathing launchers. In this one appendix the limits on preferential defenses are shown to illustrate the awkwardness of the constraints, if imposed algebraically.

Figure 19 shows R_2 as a function of x, the fraction of the attack on retaliatory forces, for I = 1,000 midcourse defenses, B = 1,000 air delivered weapons, and four values of boost phase attrition. The bombers are not varied, they are only included to produce realistic biases in the costs. The strike is assumed to have about 8,000 weapons in the absence of defenses. The boost phase defenses are assumed to reduce that number randomly by 6,000, 4,000, 2,000, and 0 RVs, as shown by the four curves. It is an interesting coincidence that all of the curves come together at x = 0.1. The maximum value of R_2 is set by the total of missile and bomber weapons less defenses, which is mM + B - I = 2,000 for this example. The minimum is set by the airborne weapons, which are assumed invulnerable once launched.

The bottom curve is for the unattrited attack. For x > 0.3 no missiles survive; the curve drops to the 1,000 weapons from the bombers. For 2,000 boost defenses the curve shifts, but not significantly. For 4,000 defenses the toe of the curve extends out to x = 0.5. For 6,000 forces, or 2,000 penetrating RVs, the toe extends all the way to x > 0.9, so that essentially all of the land missiles survive for x < 0.5. Not unsurprisingly, the extent of the targetable retaliatory forces varies from all to none over this range of boost phase defenses, which are appropriate for the first phase of defensive deployment.

Prime's goal is to minimize the overall cost of attack, Figure 20 shows the impact on prime's cost, which from the conjugate of Eq. (4) of the text is

$$C_1' = 1 - \exp(-k' \cdot R_2) + L' \cdot \exp[-k \cdot (1-x) R_1'], \qquad \text{(D2)}$$

where the fraction 1-x allocated to value is shown explicitly. The fraction allocated to damage limitation is reflected in Eq. (D1), which together with Eq. (D2) provides a complete description of prime's accounting and objective. Simply put, prime wishes to choose x so as to minimize C_1'. Ideally Eq. (D2) could be differentiated and minimized analytically, but the constraints make that awkward. Numerical solutions are used instead.

Figure 20 shows the impact on prime's cost of various choices of x. The top curve is the total C_1'; the middle is the cost of imperfect damage limiting, which falls as more RVs are allocated to unprime's retaliatory forces; and the bottom curve is the cost of value targets foregone, which increases with x as more weapons are shifted from value to retaliatory forces. The interaction of the two costs produces a shallow minimum at about $x = 0.5$. The cost to prime for operating at either extreme would be about 40% higher.

Figure 21 shows how those attacker costs vary as boost phase defenses increase for a constant I = 1,000 interceptors. The bottom curve is for K = 0, no boost defenses. It has a very broad minimum that extends over $\approx 0.3 < x < 0.7$. The minimum is down by about 40% from the values at the extremes. The curves for K = 2,000 and 4,000 form a narrower minimum, although its value does not shift much and remains at $x \approx 0.5$. The curve for K = 6,000, however, essentially flattens the cost and eliminates any minimum. If anything, there is a slight incentive to choose one extreme or the other. Overall, there is little preference at low defense levels, a slight preference for a rough sharing of targets and costs in the middle, and no strong preference against strong boost-phase defenses either.

Figure 22 shows the variation of cost with midcourse defenses for K = 4,000. The top curve on the left, the continuous arc, is for I = 500, weak defenses. It has a fairly broad but deep minimum at $x \approx 0.5$. The second curve for I = 1,000 has a different shape. It is flattened at the top and convex rather than concave. It still, however, has a minimum at $x \approx 0.5$, as does that for I = 1,500. That for I = 2,000 flattens out and has a minimum at $x = 0$.

The set of curves appears a bit perverse. Adding interceptors doesn't shift the optimum and ultimately decreases the costs of attack. The reason is that it is assumed that prime has the same number of interceptors as unprime, and those I' interceptors work with undiminished effect, while in Eq. (D1), those of I are diminished by a factor $mM/x \approx 2{,}000/4{,}000 \approx 0.5$, or eliminated altogether for I large.

The calculations discussed above give little solid guidance as to the partition of the attack between retaliatory and value targets. There are real minima in the attacker's cost function, particularly at intermediate levels of defense, but they are neither sharp nor deep enough to provide a strong allocation algorithm. The minima are certainly weak enough to be sensitive to the attacker's actual objective function, which is not known. For approximate calculations it would seem appropriate to choose a fixed value of $x = 0.5$, which is consistent with the minima from these bounding calculations, and represents an admixture of both targeting goals rather than either extreme.

APPENDIX E. TARGETING MISSILES AND DEFENSES INTERACTIVELY

The previous appendix treated the proper allocation of missile attacks and defenses in the absence of bombers. This appendix extends that analysis to their allocation when bombers are present and a significant contributor to both the first and 0.25 retaliatory strikes. The equations are straightforward, but they are strongly and intrinsically nonlinear, so analytic optimizations are difficult, particularly given the constraints that must be satisfied. Thus, the discussion here is largely a numerical demonstration that the competitive allocation of offensive and defensive assets has some basis in optimization, the values used in the text are reasonable approximations to them, and the results derived are not overly sensitive to the precise allocations made.

The basis for the analysis is the model of Appendix A, although here interest attaches to the variation of the strikes with the parameters of the attack, x and y, and the defense, g and h, rather than their variation with K or I. Figure 23 shows the variation of the strikes with x for $x + y = 0.4$, i.e., 40% of the attack is always on value and those on missiles and bombers are complementary. The abscissa is x; the ordinate is the number of strikes. The two horizontal lines are for R_1 and R_1', which do not vary with x. The two curves are for R_2 and R_2'.

If prime is the attacker his goal is to minimize R_2, which is done by a choice of $x \approx 0.25$. The calculations were done for the nominal $g = h = 0.3$, which means that the fraction x of the attack on missiles with which prime minimizes R_2 is about equal to the value of g with which unprime maximizes it. As g is varied from 0.1 to 0.5, the value of x that minimizes R_2 shifts to stay roughly equal to it. More important than the specific values, however, is that the minimum is broad and not very deep. The difference in R_2 is from 1,500 to 1,900 weapons over the interval shown. Thus, it is not necessary to get the absolute minimum or the value of x precisely right.

The curve for R_2' shows that insensitivity also holds if unprime is the attacker. The minimum is at $x \approx 0.15$, but the penalty, or gain, for choosing 0.3 would be less than 10%. Since the benefits of operating at extreme values are small and the penalties could have uncertainties, it is not inappropriate to devote roughly equal fractions of the attack to missiles, bombers, and value. Similar allocations of defenses are not necessarily optimal, but they involve small penalties and avoid the possibility of extreme allocations of the attack. Similar insensitivities hold for other values of K and I.

Figure 24 shows the costs associated with those values of x. They are relatively flat, although C_1 and C_1' do have broad minima at about 0.15 and 0.25, respectively. The costs of operating off optimum are small. Figure 25 shows the stability indices have greater variation. For the reasons described above the individual indices and the compound index have minima at $x \approx 0.2$. That is because minimizing the other's second strike tends to reduce stability. Over the interval x = 0.1 to 0.3, however, the variation is less than 10%, which is small compared to the variations due to changes in K and I studied in the text.

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Fig. 1. Prime midcourse RVs (R1m′)

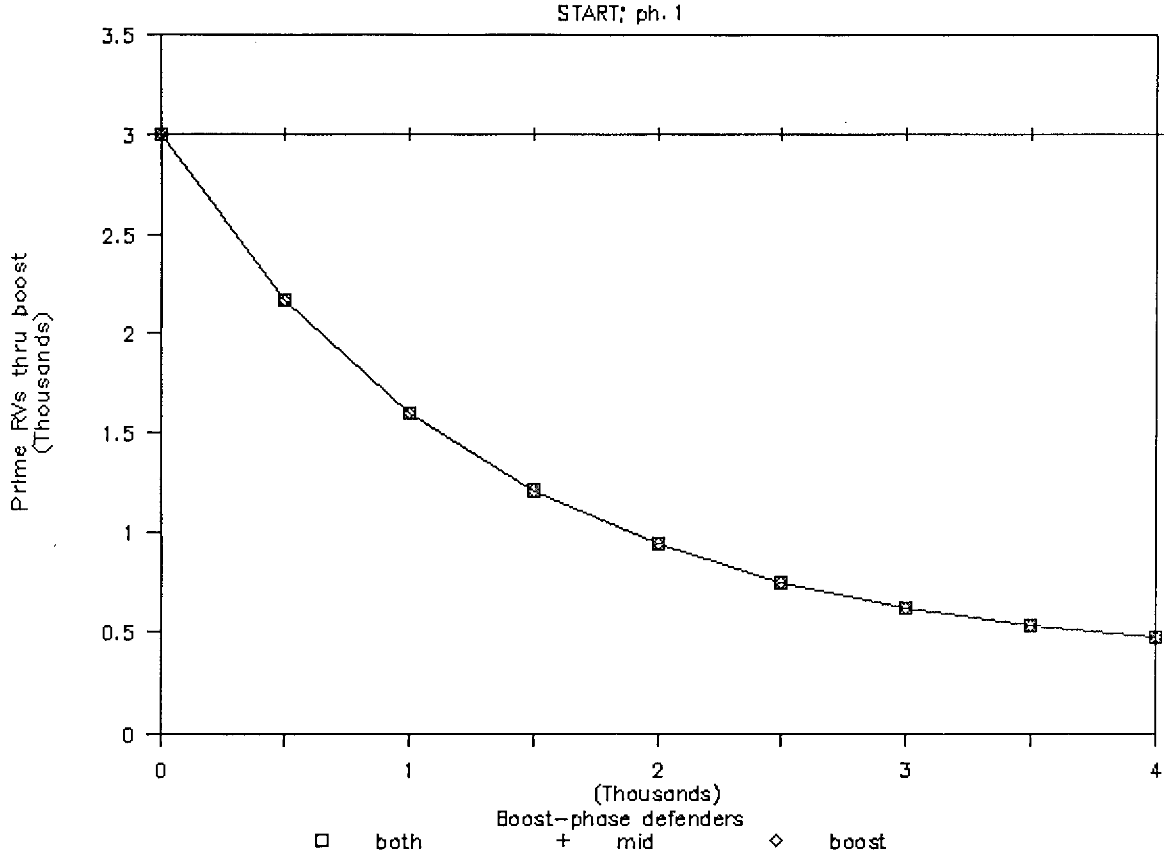


Fig. 2. Prime SLBM RVs thru boost (R1n′)

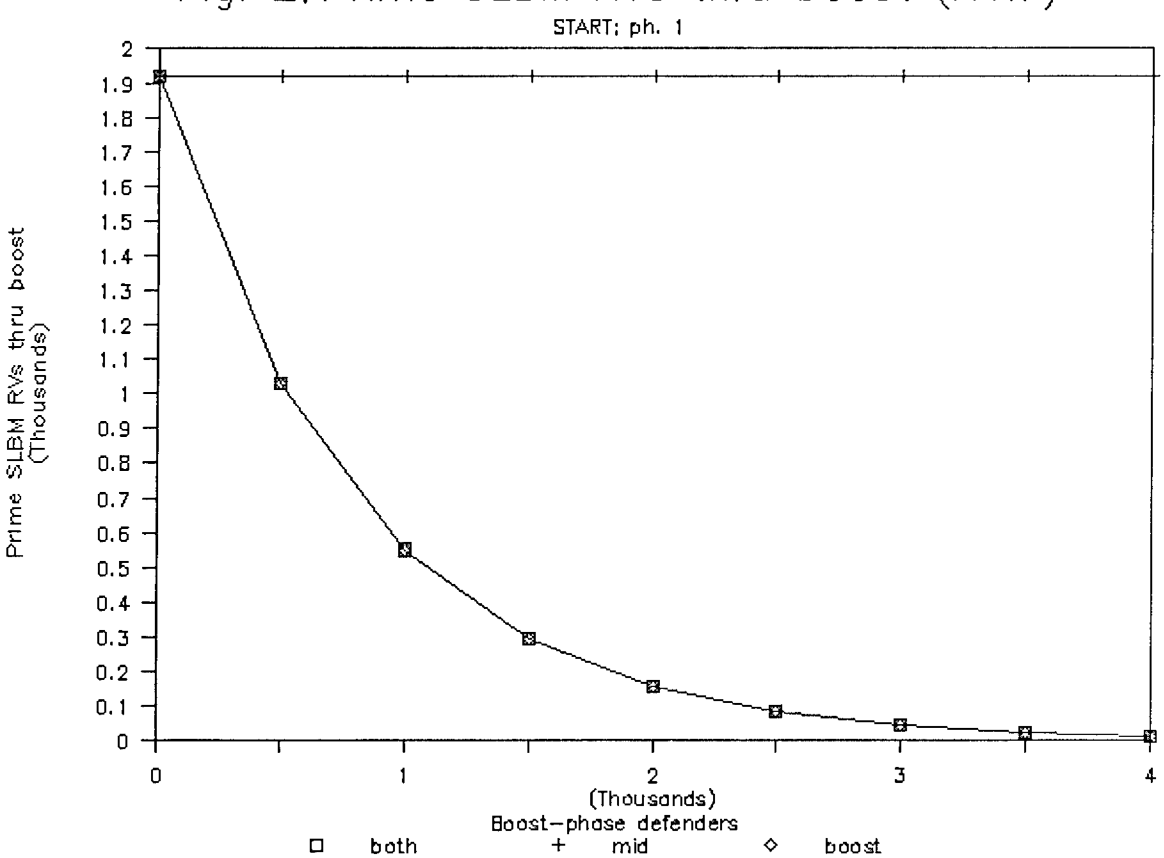


Fig. 3. Surviving unprime missiles (Ms)

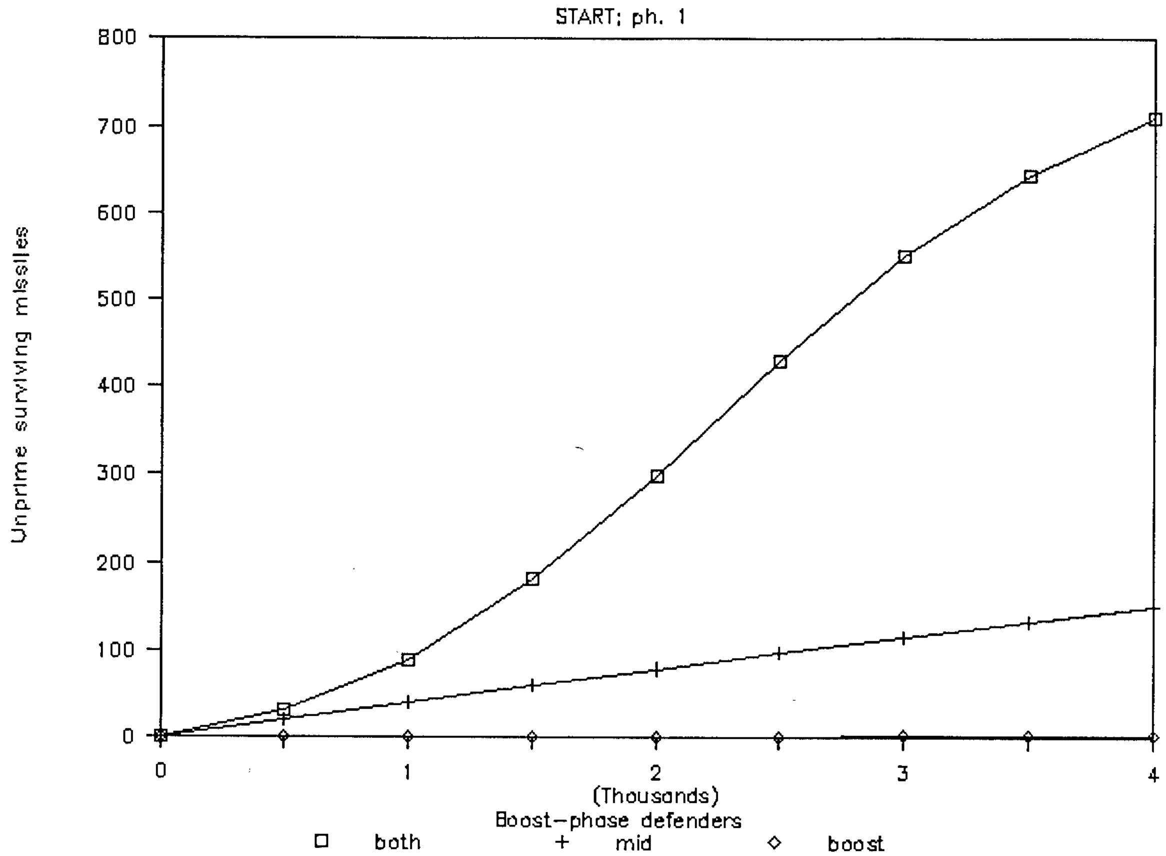


Fig. 4. Unprime bombers surviving (Bs)

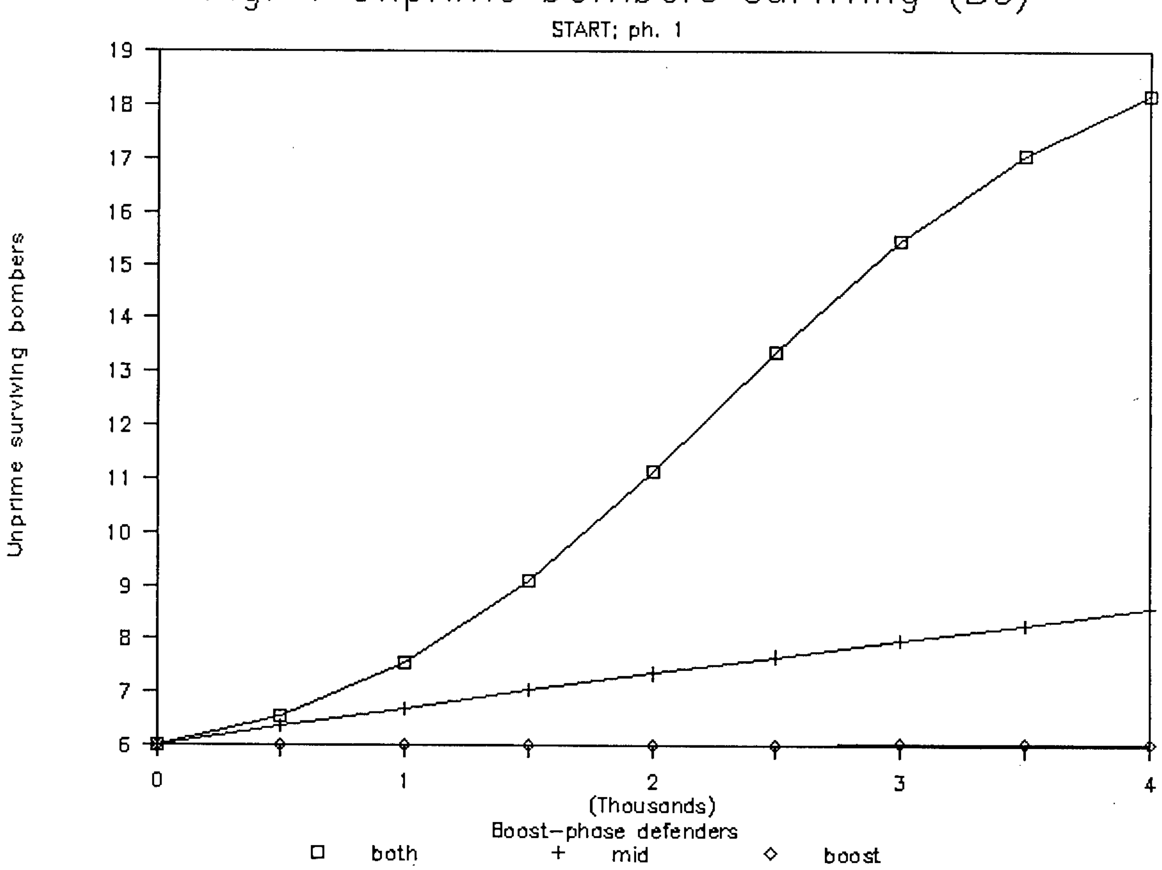


Fig. 5. Unprime ICBM RVs thru boost(R2m)

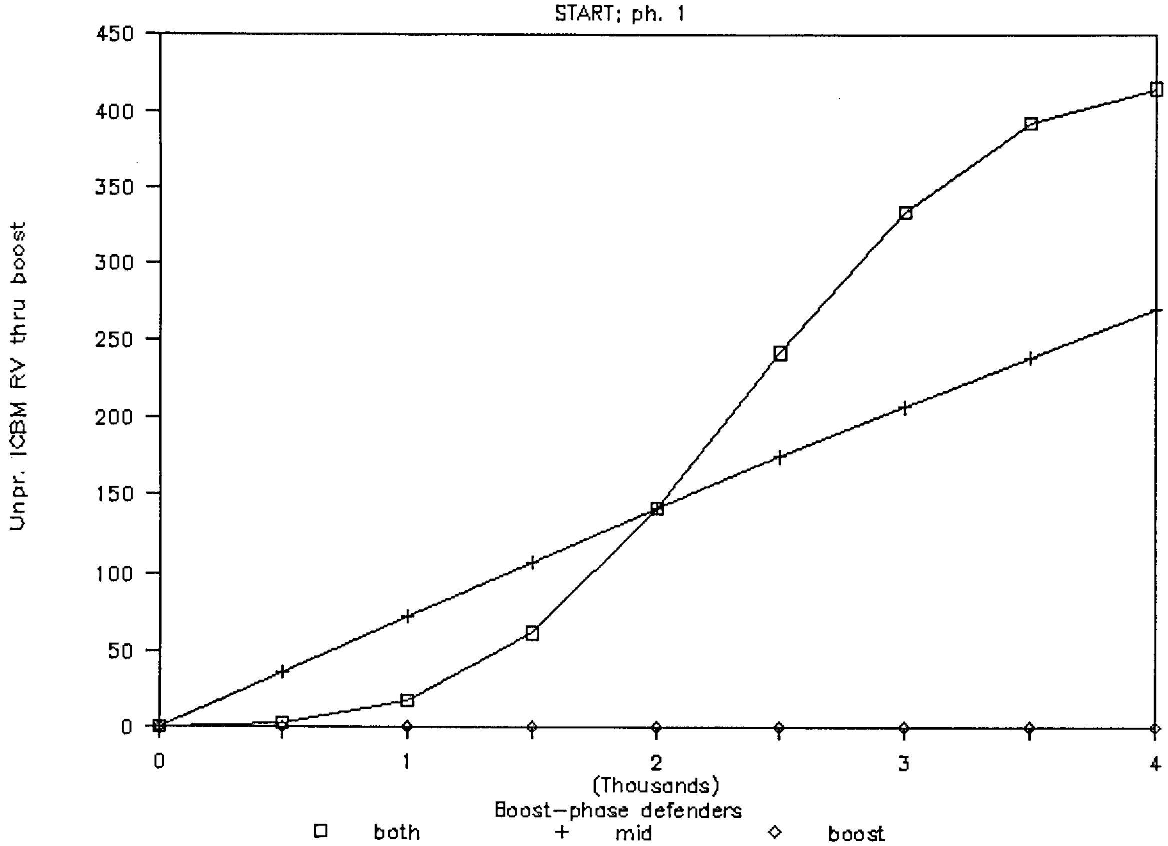


Fig.6.Unprime SLBM RVs thru boost (R2n)

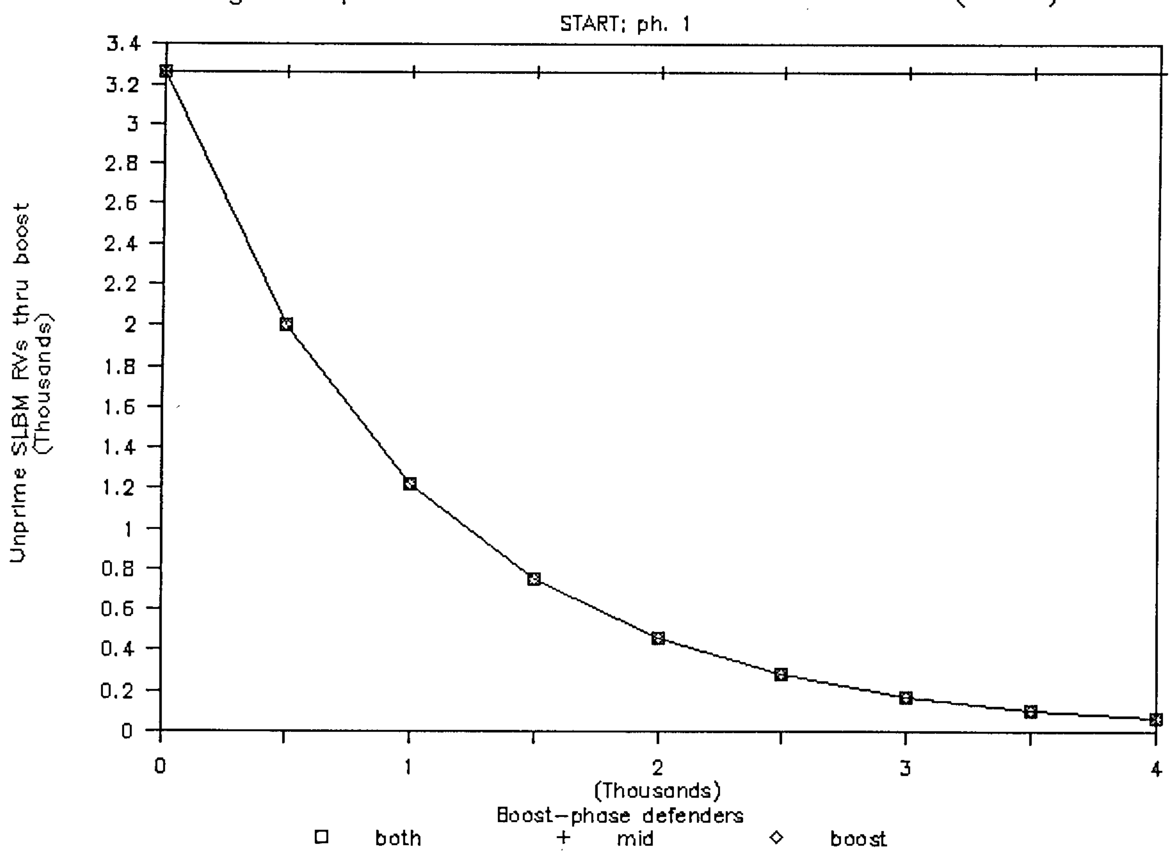


Fig. 7. Unpr RVs to value targets (R2p)

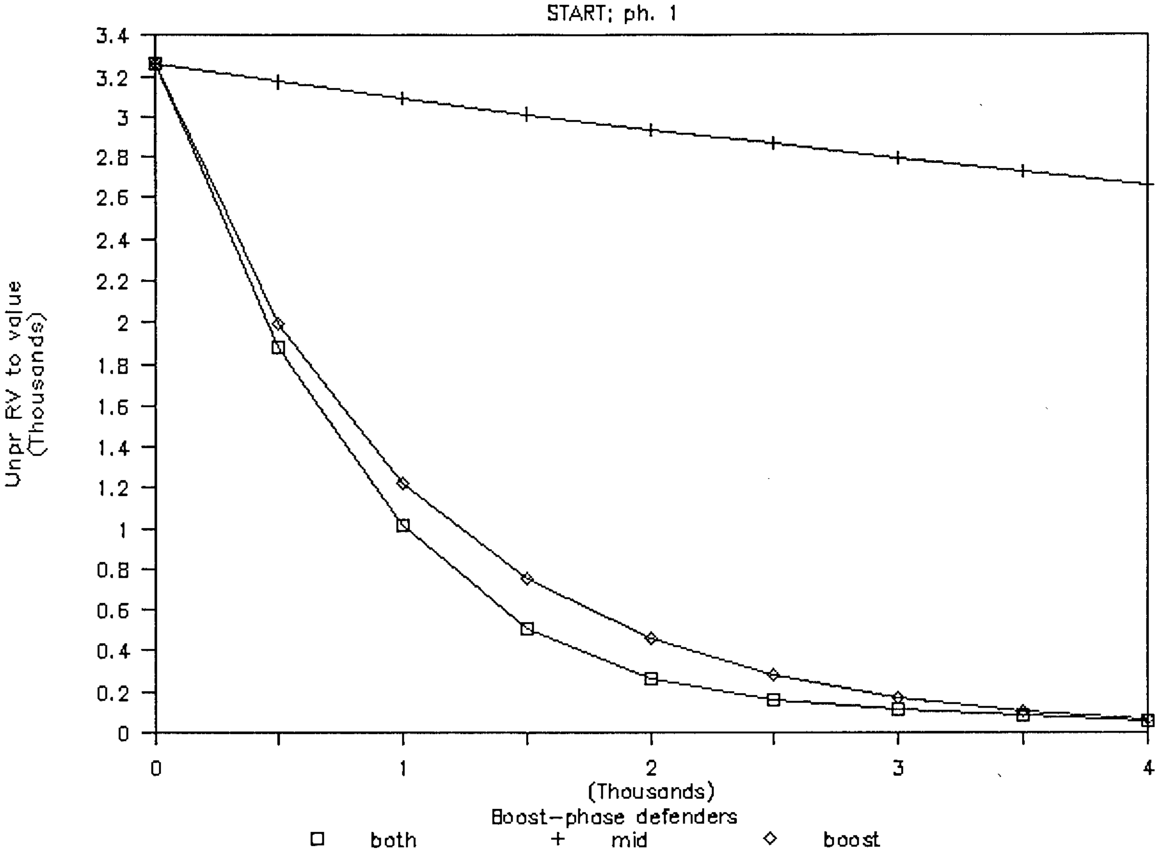


Fig. 8. Strikes on unprime value (dV1m')

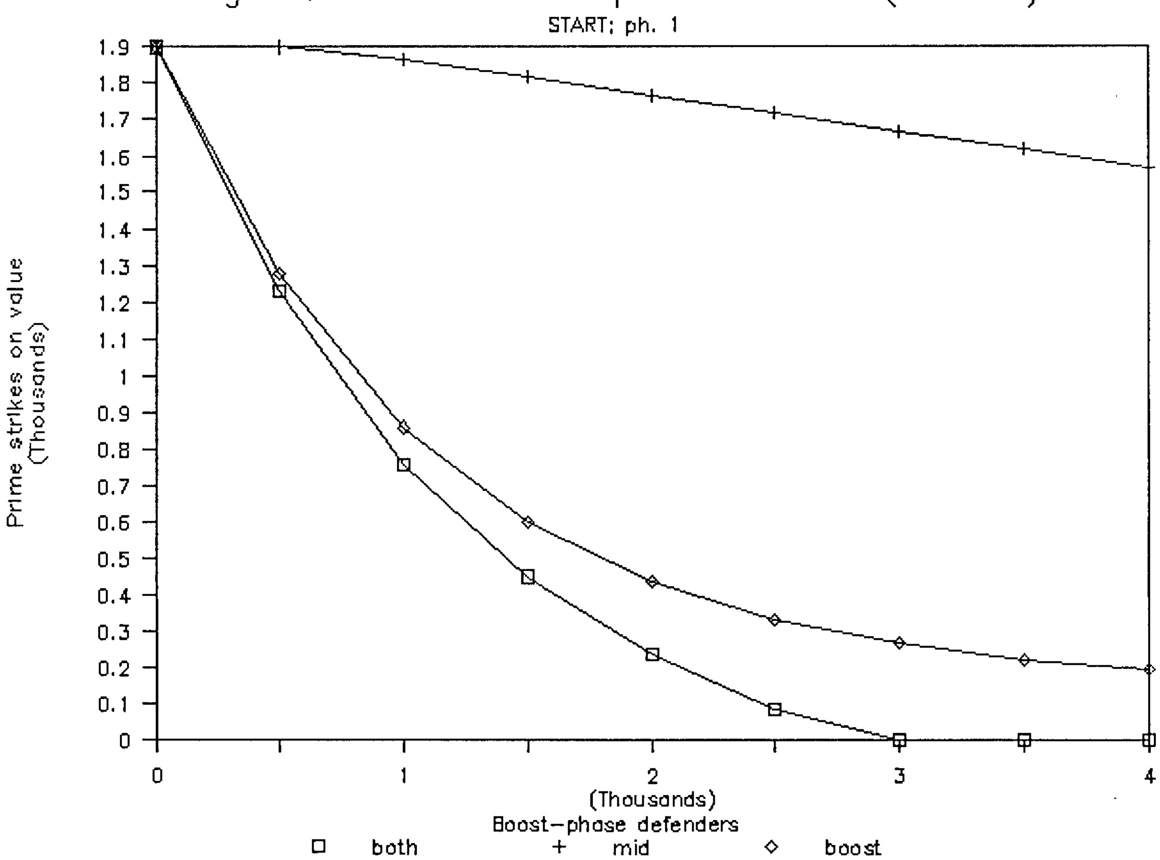


Fig. 9. Value strikes boost phase only

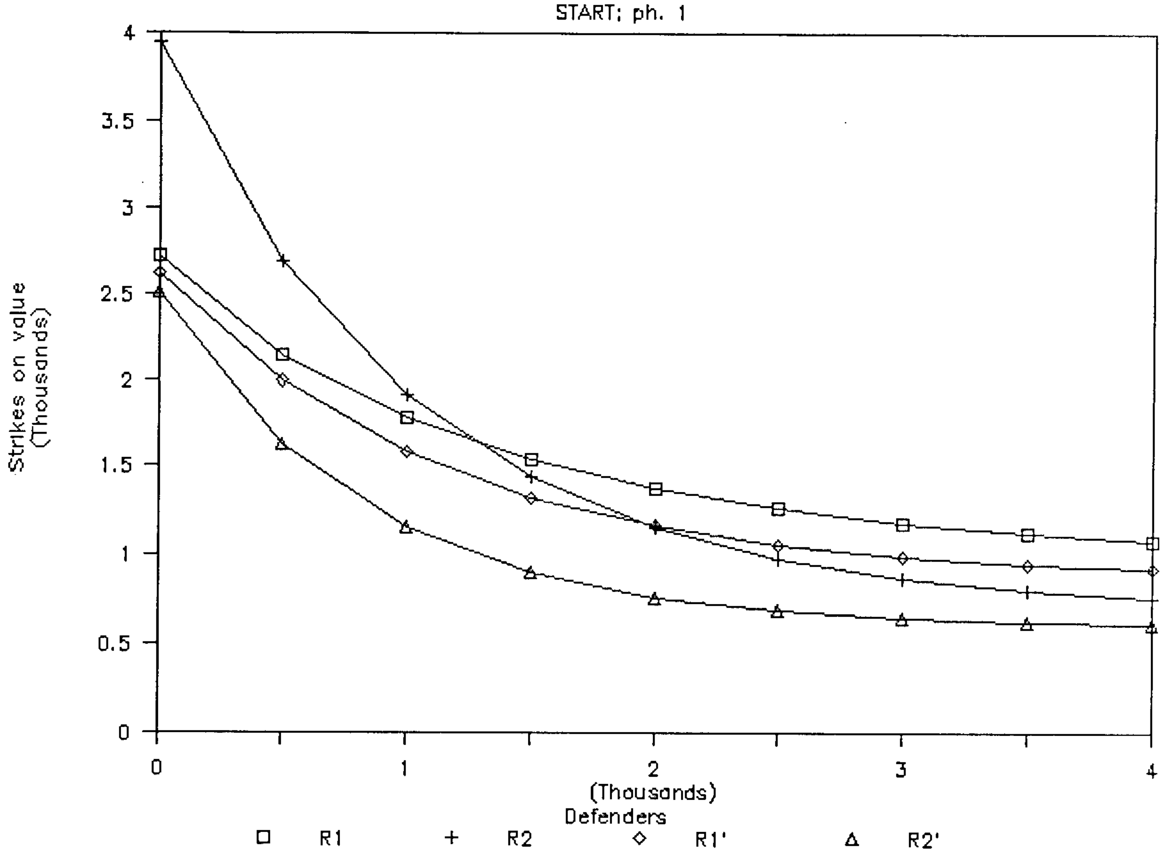


Fig. 10. Value strikes for both layers

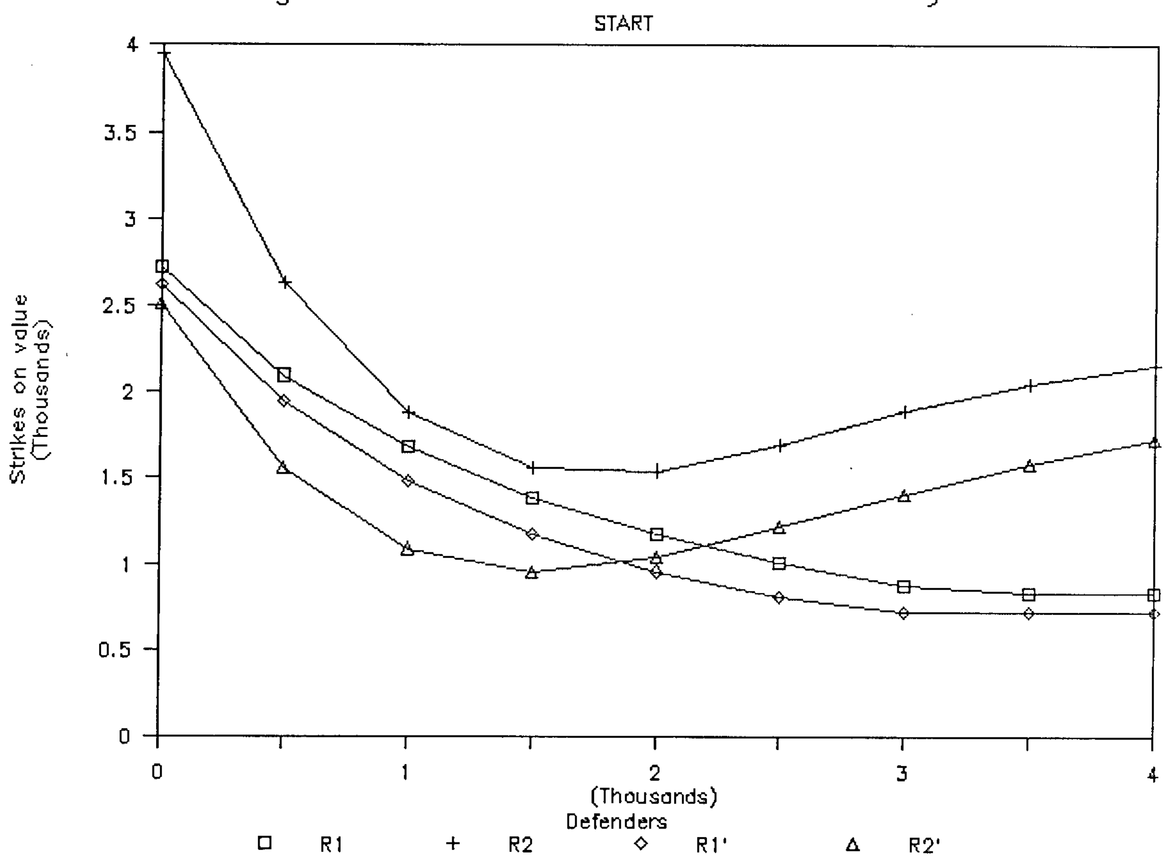


Fig. 11. Strike costs for boost only

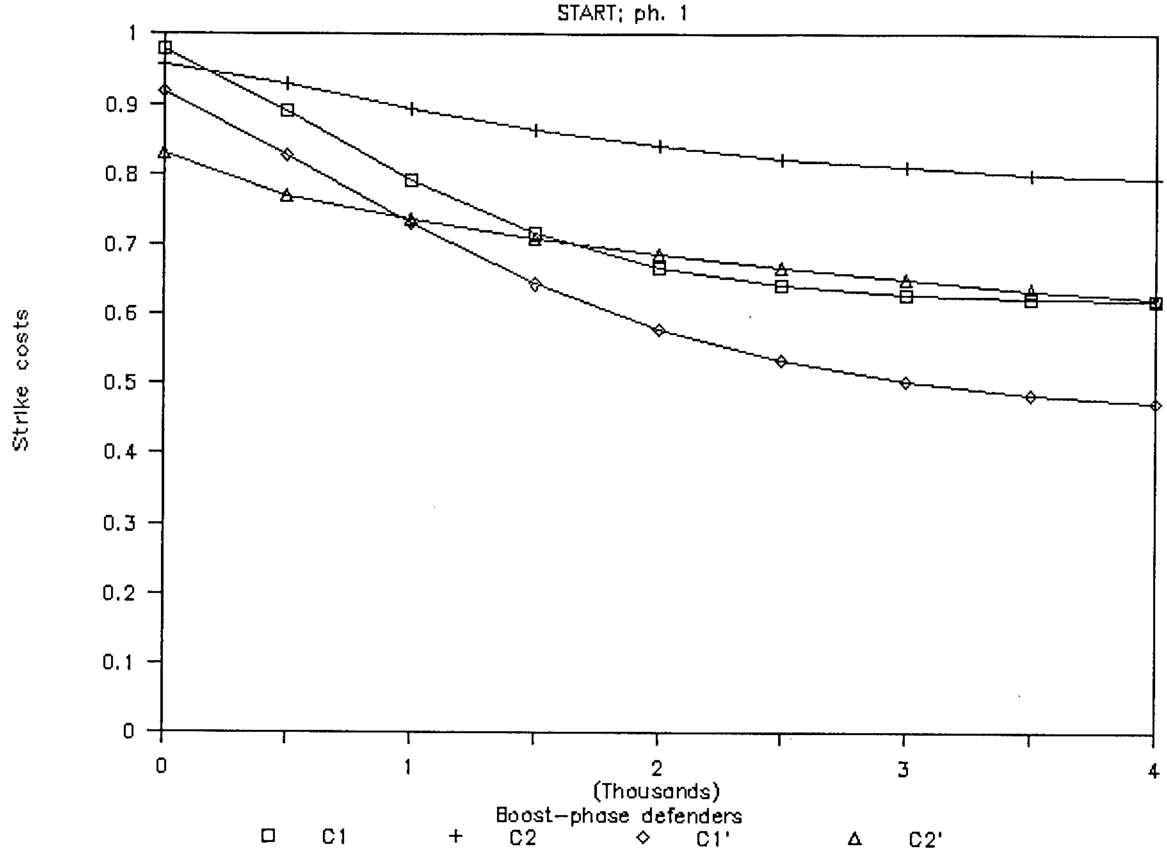


Fig. 12. Strike costs for both layers

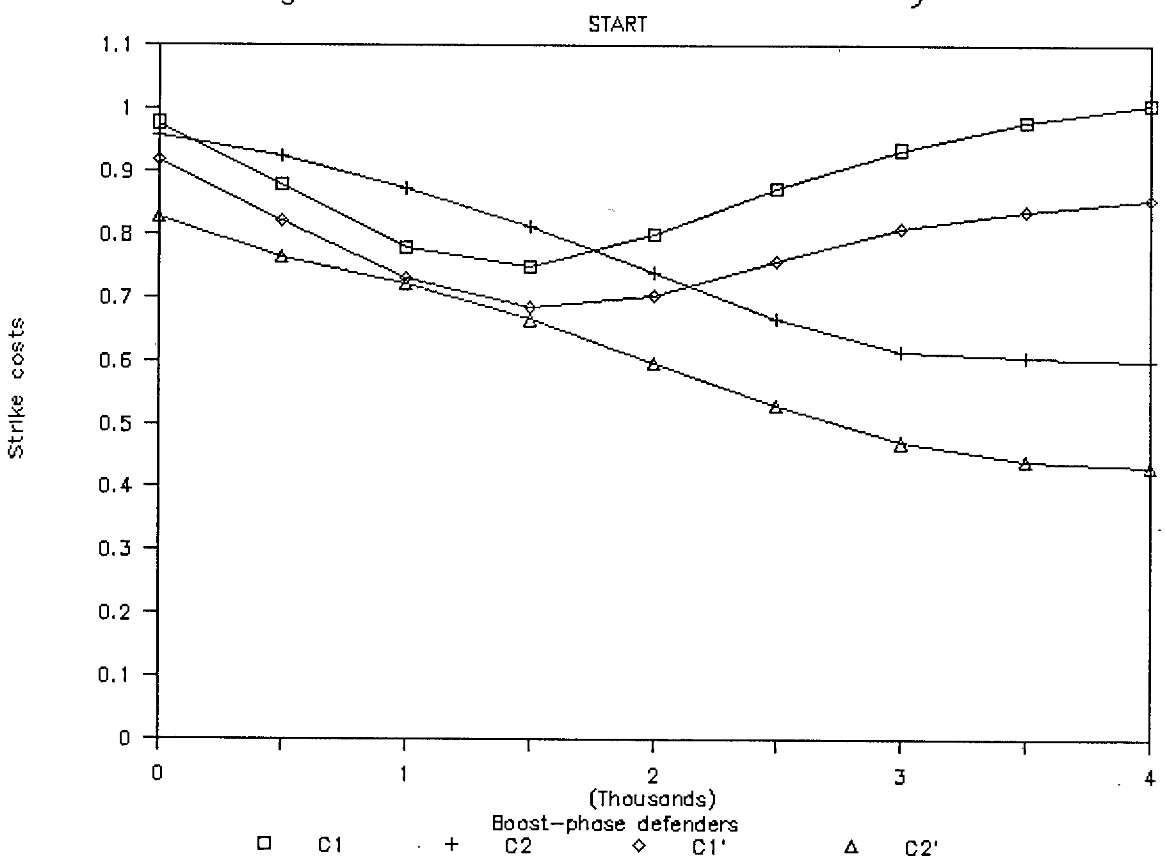


Fig. 13. Stability indices for boost

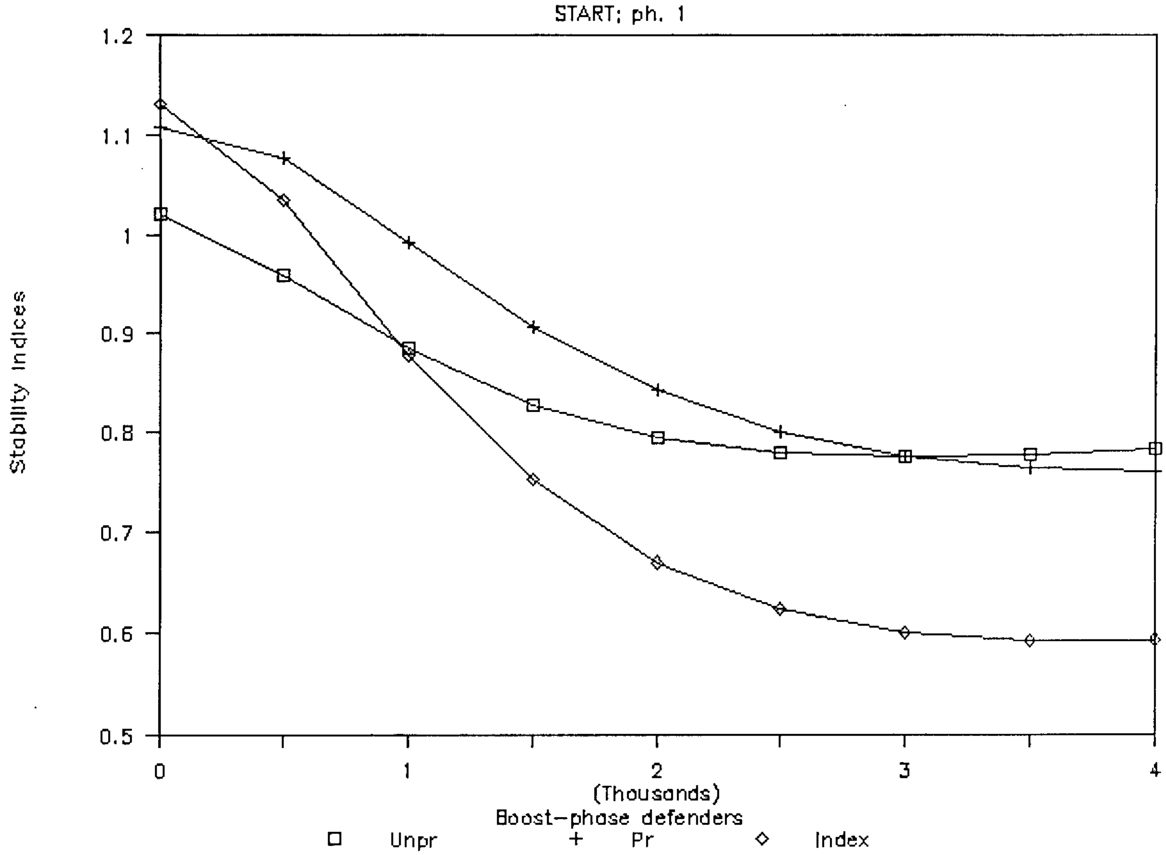


Fig. 14. Stability indices vs layers

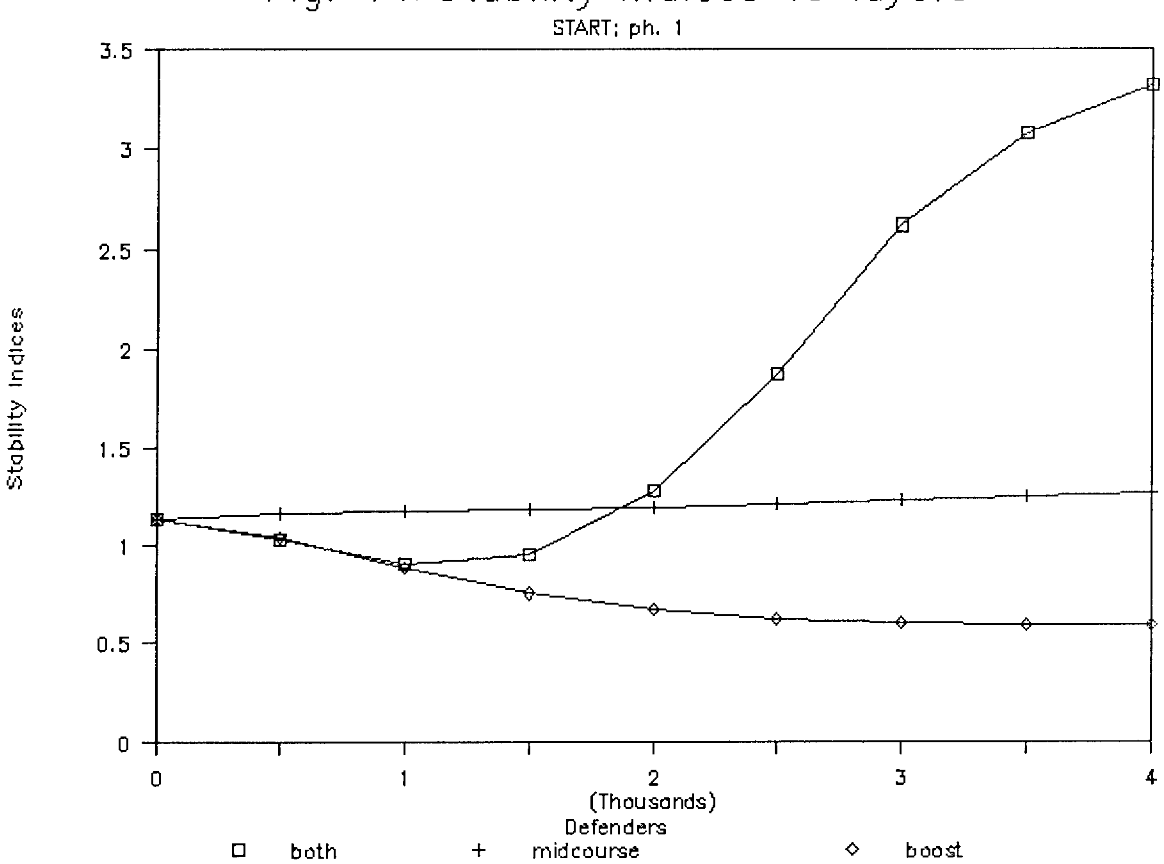


Fig. 15. Restrikes for midcourse layer

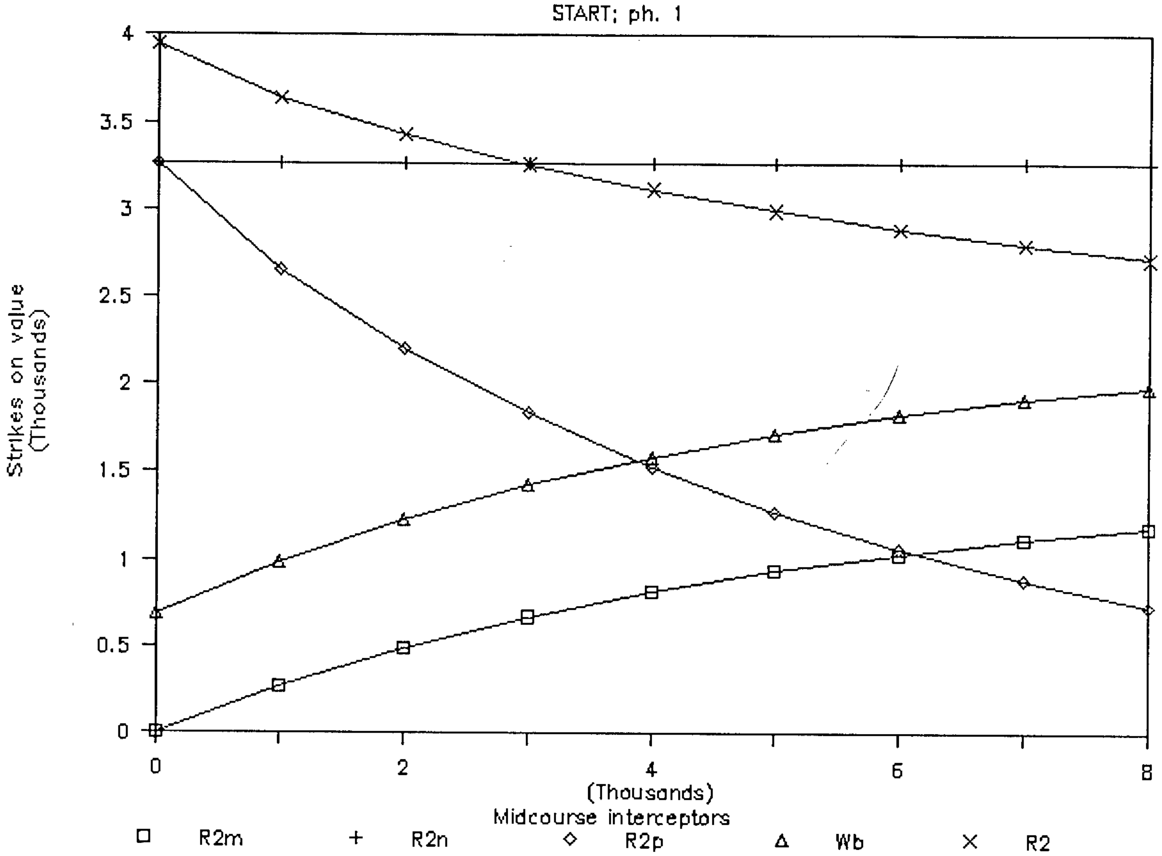


Fig. 16. Value strikes for both layers

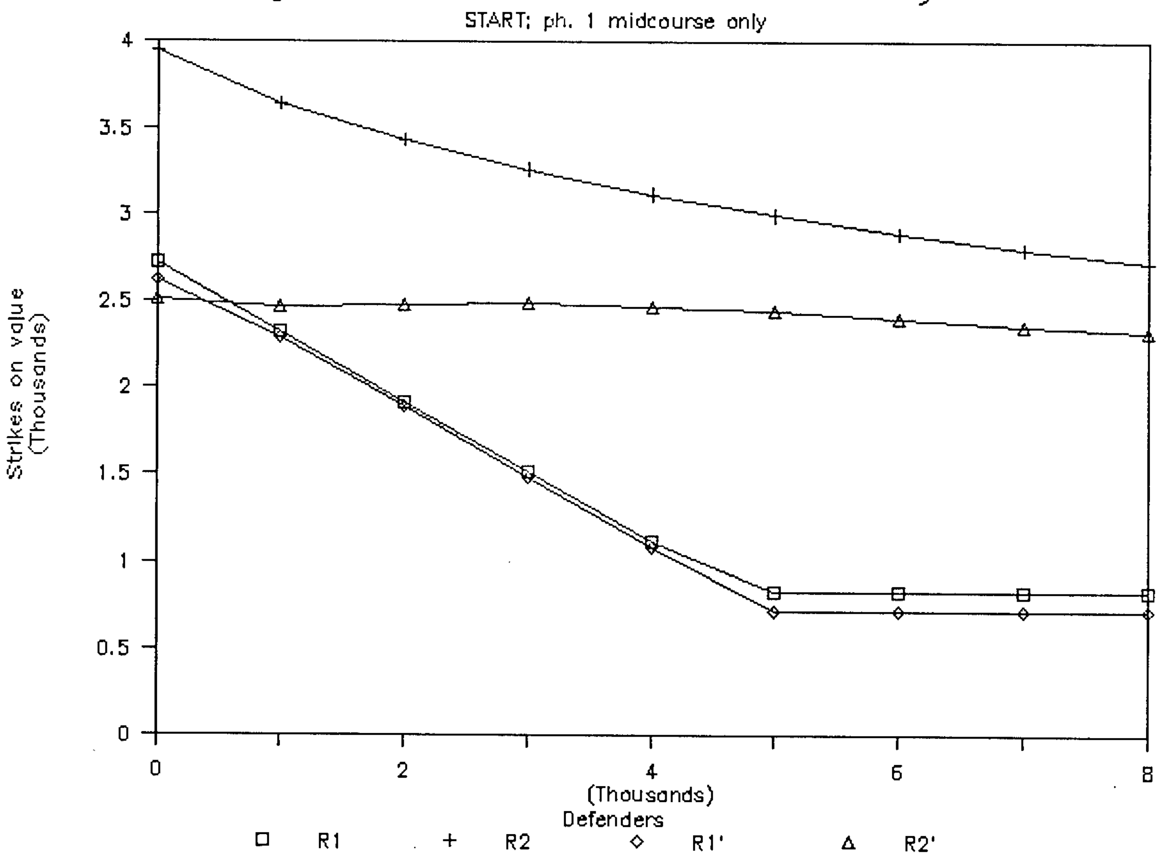


Fig. 17. Costs for midcourse defense

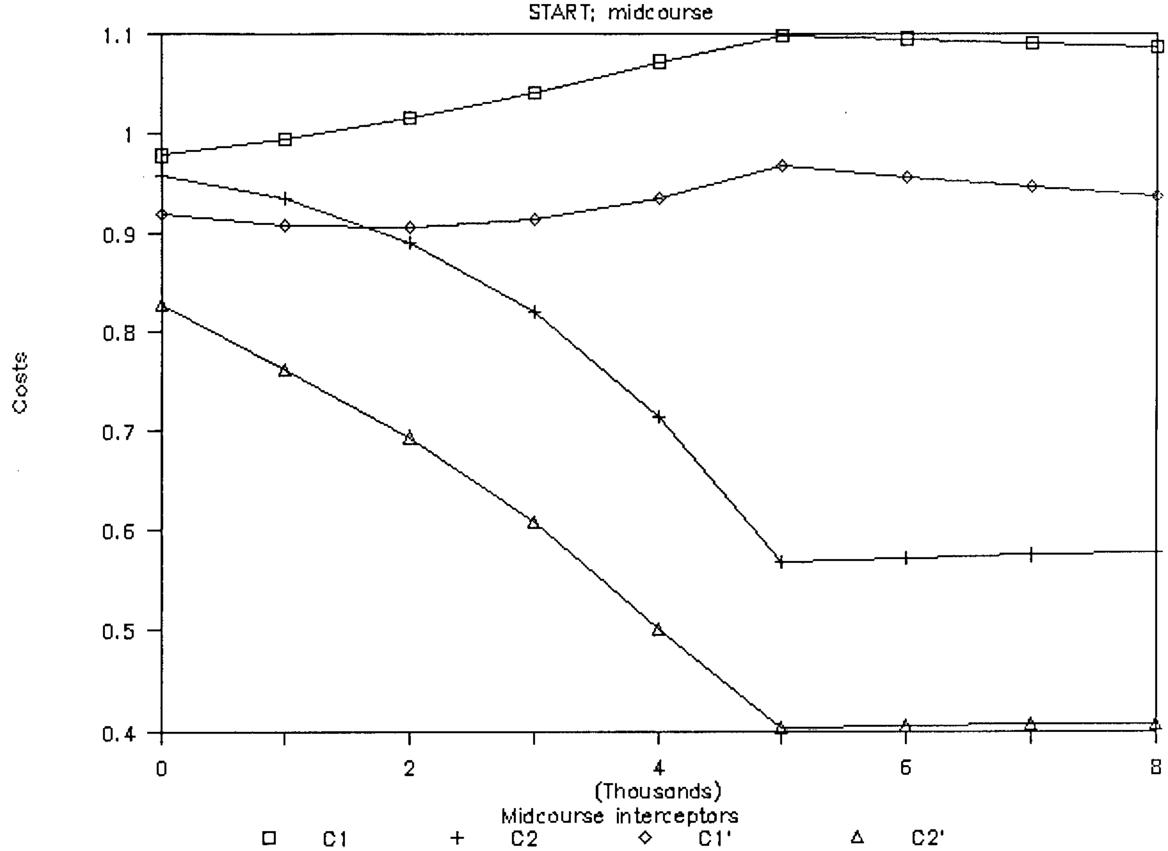


Fig. 18. Stability of midcourse defense

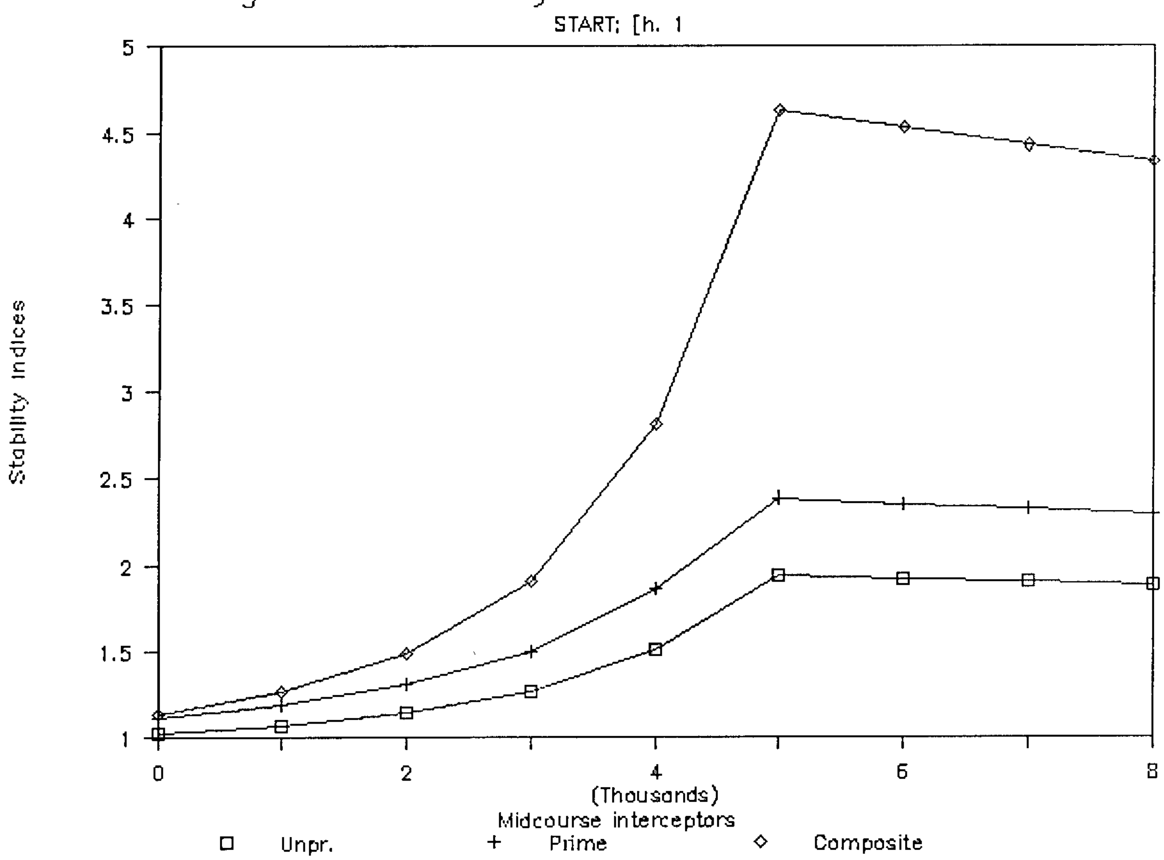


Fig. 19. Retaliatory forces vs attack

m=2,M=1K,I=1K,B=1K

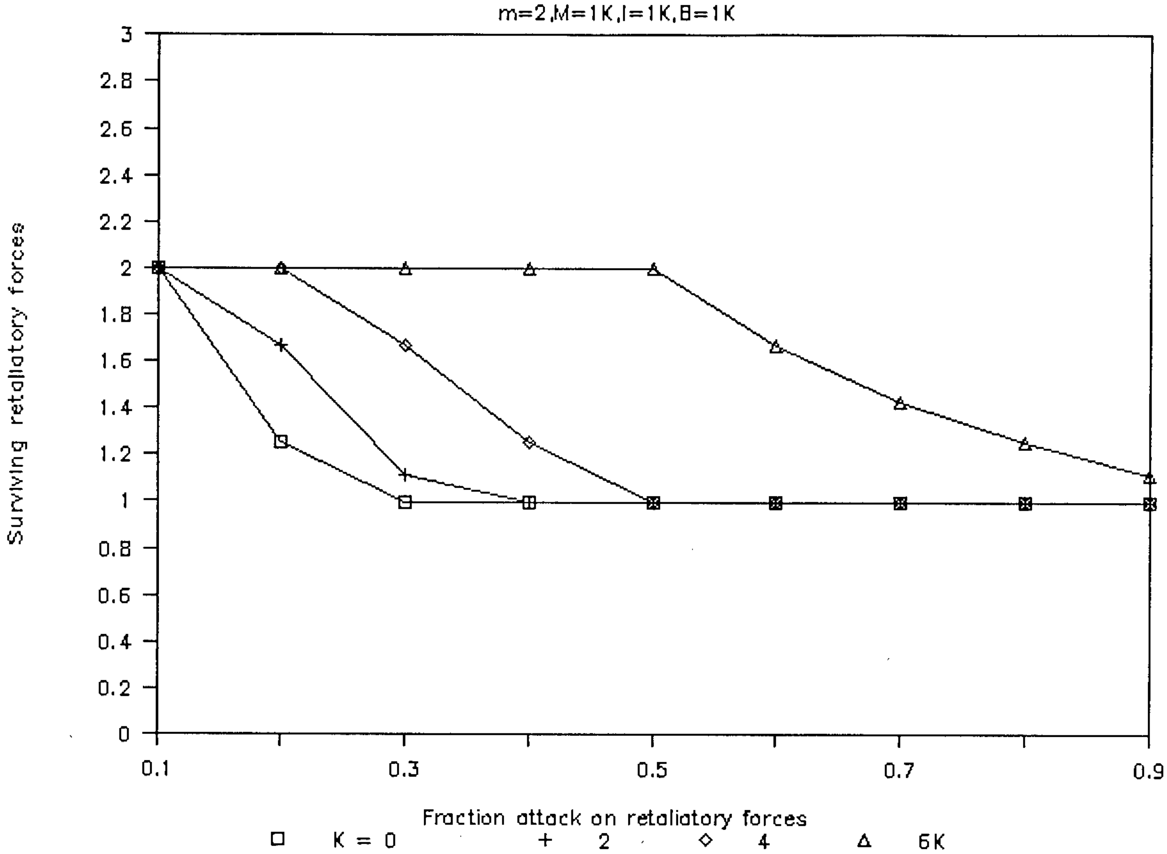


Fig. 20. Cost to first striker

m=2,M=1K,I=1K,B=1K

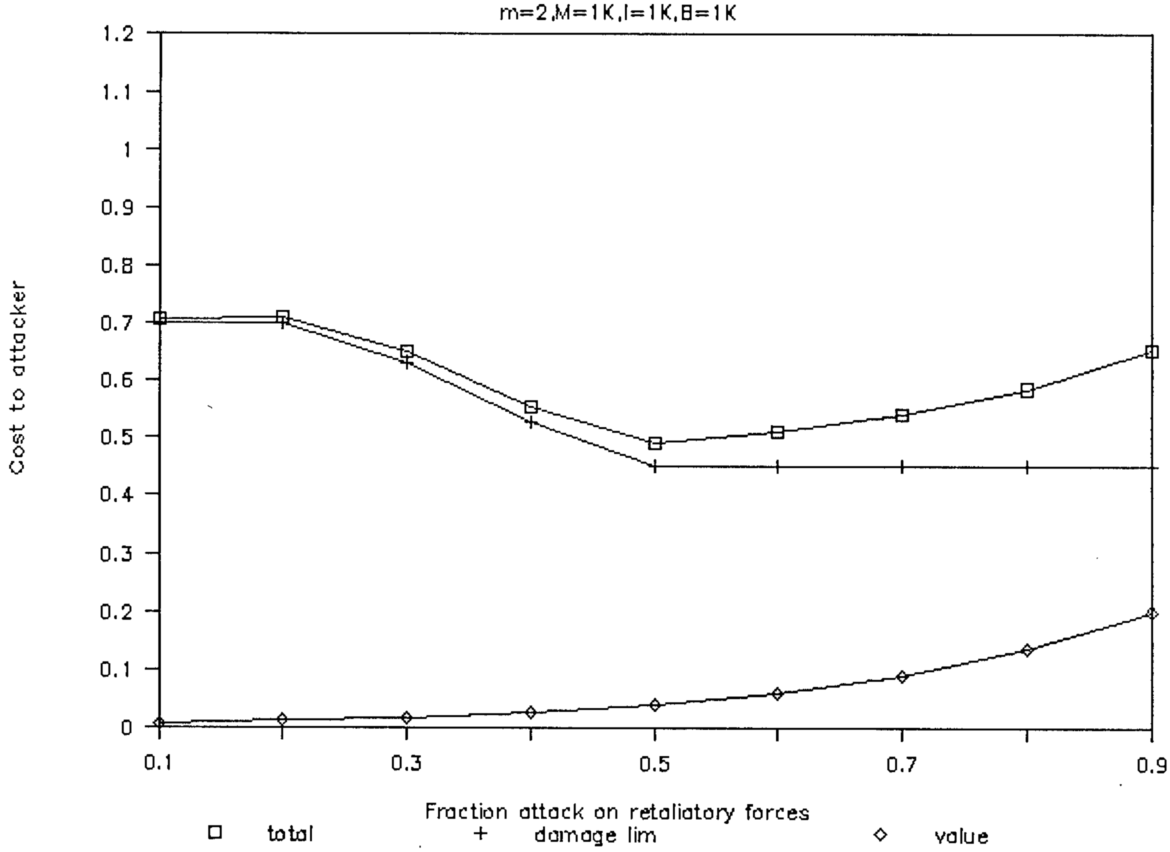


Fig. 21. Cost vs boost phase attrition

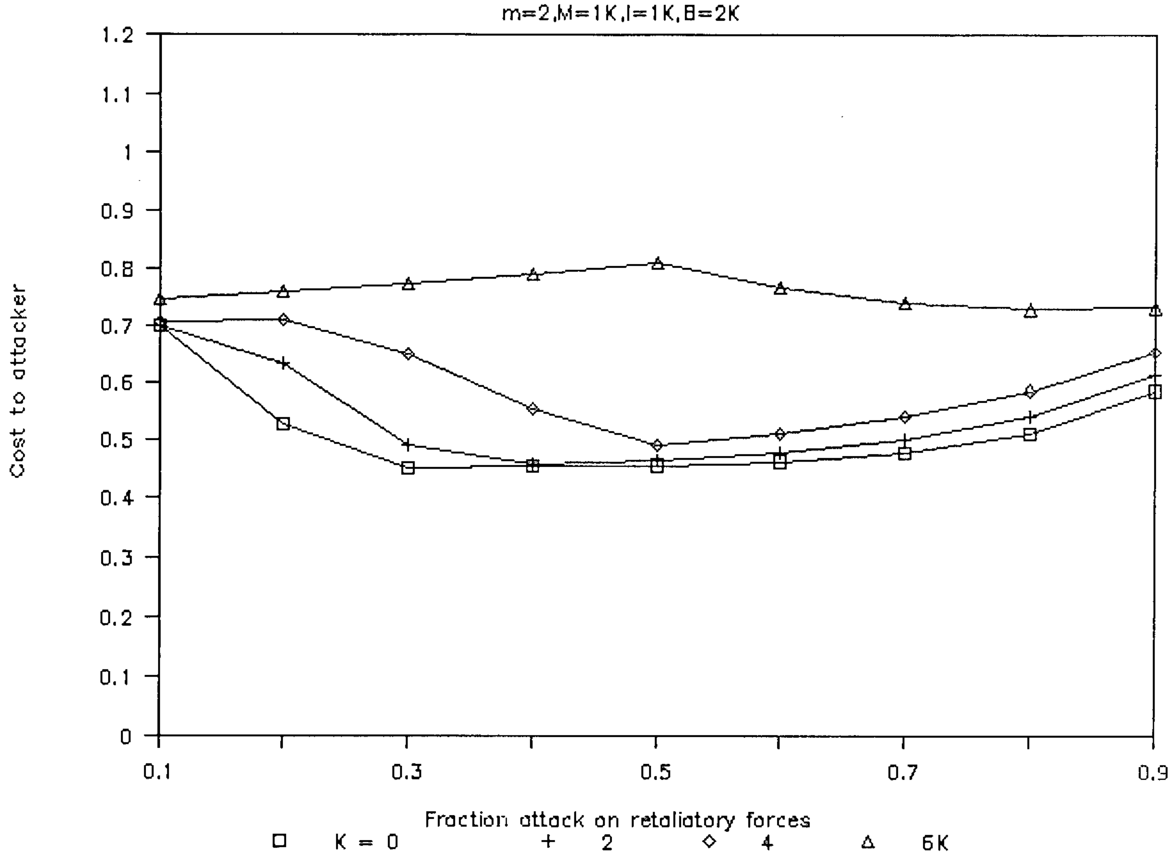


Fig. 22. Cost vs midcourse attrition

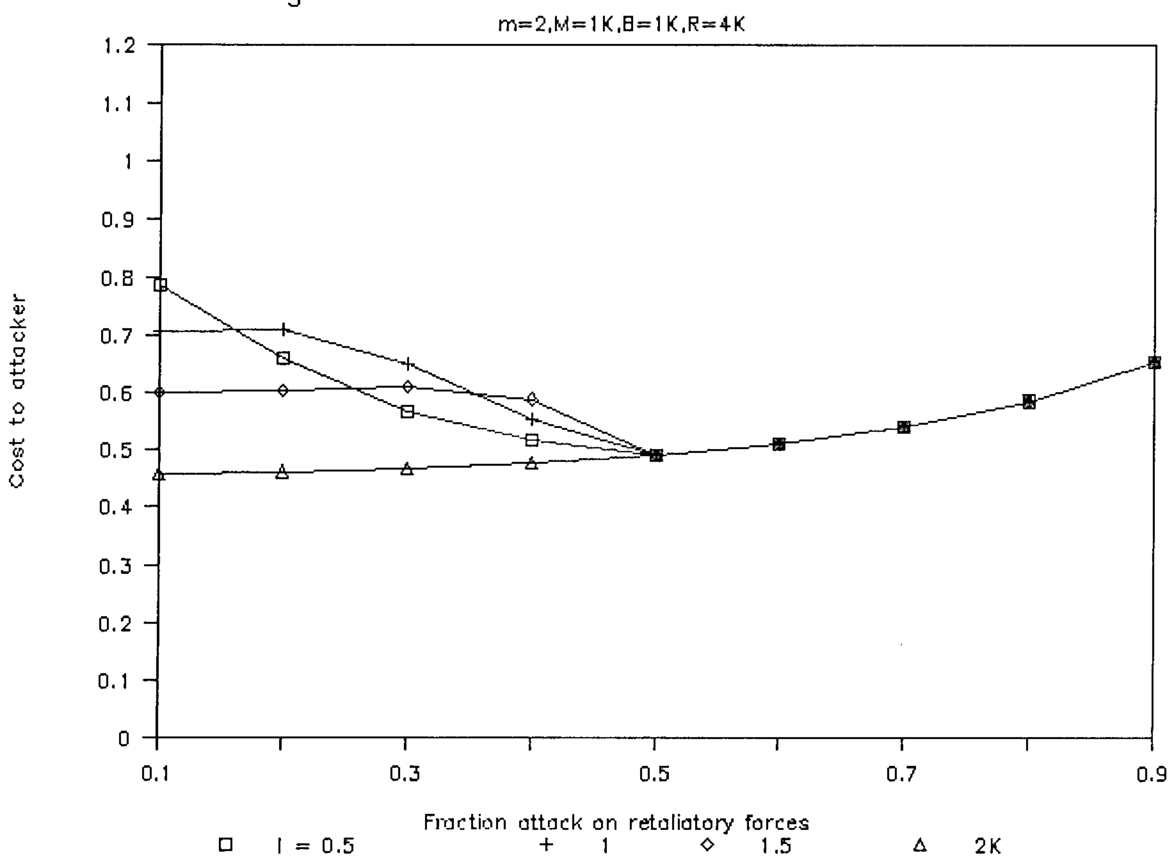


Fig. 23. Value strikes for combined def

START,g=h=0.3,x+y=0.6,K=2000,l=500

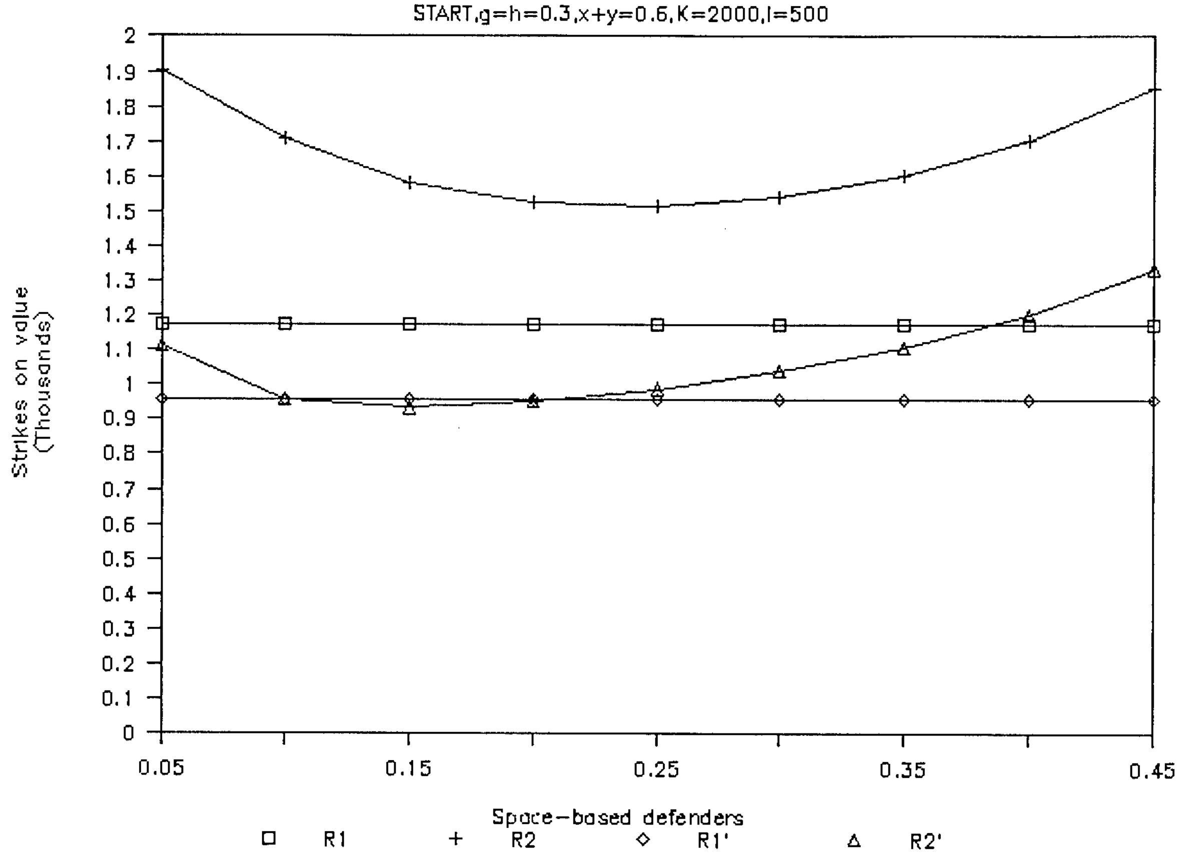


Fig. 24. Costs vs attack allocation

START, nominal def.

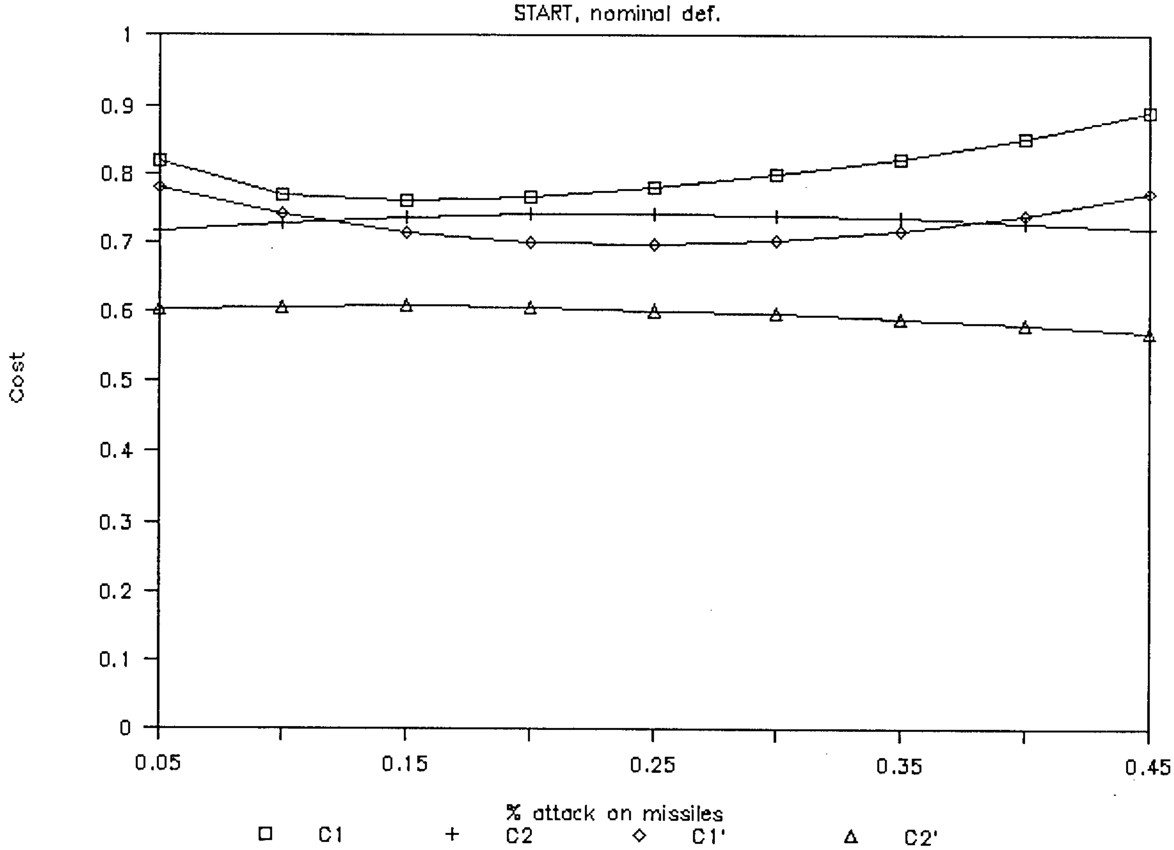


Fig. 25. Stability indices vs allocation

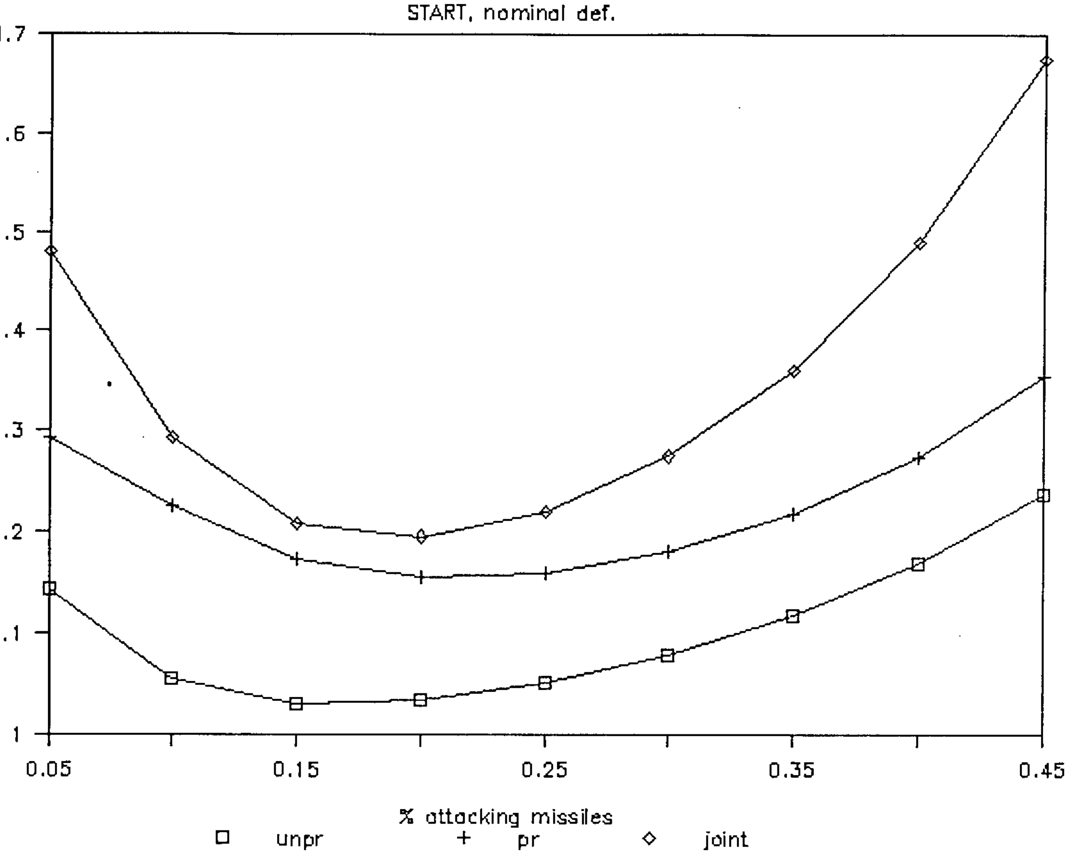
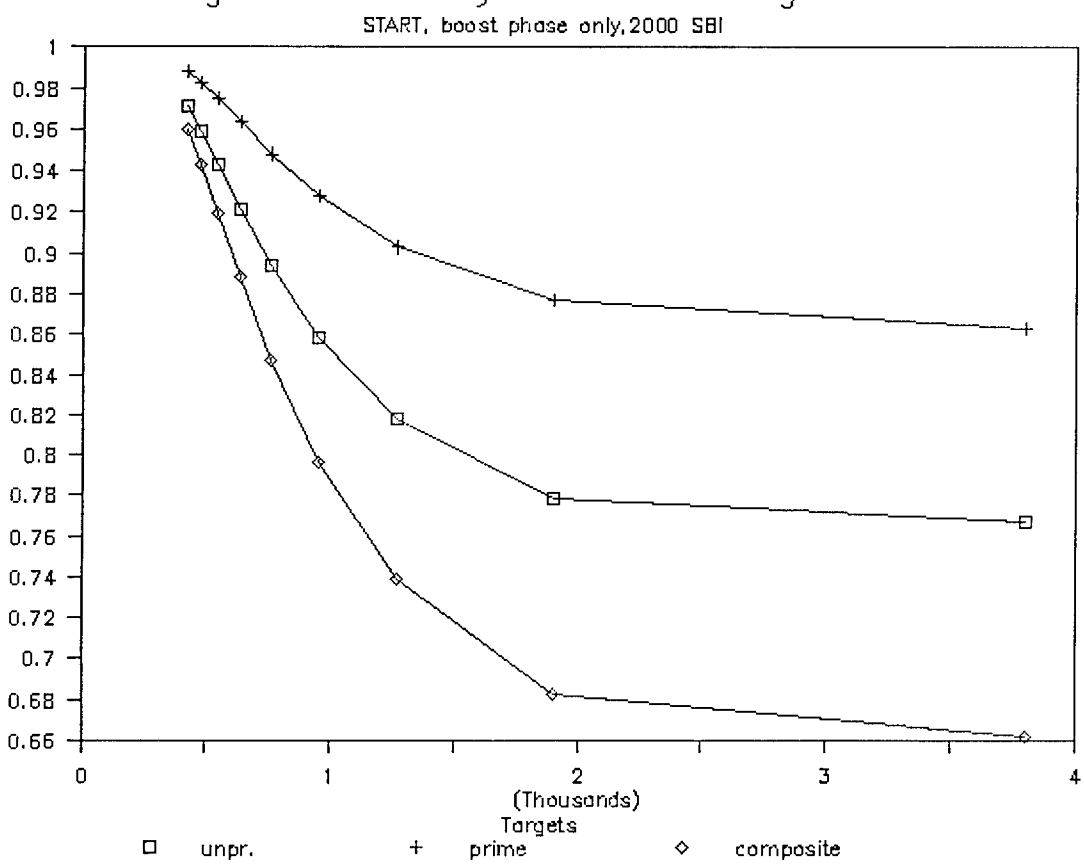


Fig. 26. Stability index vs target set



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