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Role of Terminal Defenses in Strategic Defense

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ROLE OF TERMINAL DEFENSES IN STRATEGIC DEFENSE

by

Gregory H. Canavan

ABSTRACT

Terminal interceptors can use the atmosphere for discrimination. They also have disadvantages in development, cost, saturation, and susceptibility to preferential attacks. Terminal could be preferred for higher midcourse costs or decoys. Their main limitation is battlespace. It is possible to integrate boost- and terminal-phase defenses by reducing the number of reentry vehicles penetrating the boost phase to the roughly one per target terminal defenses could handle. Terminal defenses could offset boost-phase defenses' lack of preferentiality and midcourse defenses' sensitivity to decoys.

I. INTRODUCTION

Terminal interceptors exist but are not always included in multi-layer analyses. This note gives a simple criterion for their inclusion. Terminal interceptors have certain advantages, such as atmospheric discrimination of decoys, but they also have disadvantages such as cost, saturation, and susceptibility to preferential attacks. They would not be used for current costs but could be effective for higher midcourse costs or decoys.

The criterion for shifting from midcourse to terminal interceptors is found to be that the number of decoys per reentry vehicle (RV) be about 12 for current costs and objectives. The main limitation on terminal interceptors is battlespace, which could limit them to about one intercept over each target. If effective, however, they could be added as a one-intercept layer, and the remaining attrition needed could be built up from midcourse or boost-phase interceptors. For strategic arms reduction talk (START)-limited offenses either combination could be effective, the former for value and the latter for hard military targets.

II. ANALYSIS

This note treats combinations of midcourse and terminal interceptors to treat the R residual weapons that penetrate boost-phase defenses. Boost phase optimization and penetration is treated in a companion note.[1] Midcourse interceptors are assumed to act preferentially and have long enough ranges to cover the whole target set. Taking them to act adaptively as well would improve performance at low levels but would not be consistent with the sensors likely to be available in the near and midterms when terminal interceptors could compete.[2]

A. Midcourse

If R penetrating weapons attack N targets, there should be $\approx$ R/N RVs per target. Thus, by committing R/N interceptors to it, any given target could be defended. I interceptors could defend $S = I/(R/N) = N(I/R)$ targets, a fraction $\Gamma = S/N = I/R$ of the total set. The choice of Γ is judgmental. It is sufficient to observe that $S \approx 300$ surviving missiles out of the $N \approx 1{,}000$ deployed, which would represent a robust deterrent, corresponds to $\Gamma = 0.3$.

If there are D decoys per RV there would be a total of (1+D)R threatening objects, so I interceptors could defend

$$S = I/[(1+D)R/N] = N[I/(1+D)R] \qquad (1)$$

targets, or a fraction $\Gamma = I/(1+D)R$ of them. D means the

credible decoys left after discrimination sensors have removed all they could. Heavy missiles could deploy about 100 decoys per RV, although the optimum is only about 20-40 when payload removal is optimized against penetration.[3] If 20-40 decoys per RV were filtered through near-term sensors capable of eliminating about half of them, D ≈ 10-20 credible decoys would remain. The attacker could obviously deploy more than 20. It is not clear that near-term discriminants could eliminate more than half.

B. Terminal

Terminal interceptors are assumed to be perfect, have complete discrimination, and have no battlespace limitations on the number of interceptors per RV. None of these assumptions is good to much better than a factor of two, but it is shown below that the results are not overly sensitive to them, and they simplify the presentation.

Facing R weapons alone, T terminal interceptors would remove T of them, leaving R - T weapons to be deposited on the targets. Less than R/N - 1 terminal interceptors wouldn't protect any targets because they can only protect adjacent targets. Worse, against terminal interceptors the attacker could attack preferentially. For T/N terminal interceptors per target, the attacker could, by committing T/N + 1 RVs, kill any selected target. With R weapons he could kill

$$K = R/(T/N + 1) \qquad (2)$$

targets up to the total of N. The offense's ability to preferentially attack terminal defenses is essentially the complement of the defenders ability to use long-range midcourse interceptors to preferentially defend uniformly attacked targets.

C. Composites

If both midcourse and terminal interceptors are deployed, they act sequentially. Of the (1+D)R/N credible objects approaching one of S protected targets, the I/S midcourse interceptors defending it could remove at best I/S objects. As the remaining (1+D)R/N - I/S objects passed through the atmosphere,

it would filter out the decoys, reducing the number of objects by a factor of $1/(1+D)$ and leaving $\approx R/N - I/(1+D)S$ weapons. The number of terminal interceptors per missile, T/N, must be as great as this, or

$$T/N = R/N - I/(1+D)S, \tag{3}$$

which can be inverted to give the number of midcourse interceptors needed, which is

$$I = (1+D)(R-T)\Gamma, \tag{4}$$

which differs from the midcourse-only result of Eq. (1) only by the subtraction of T from R, which reemphasizes the fact that T must be comparable to R to have any impact. Terminal deployments must be large because, absent mobility, they have to cover all targets--not just those saved.

D. Costs

If costs are linear in the number of interceptors, the cost of a midcourse interceptor about $\alpha \approx \$2M$, and the cost of a terminal interceptor like HEDI about $\beta \approx \$7M$,[4] then the total interceptor cost can be written as

$$C = \alpha I + \beta T, \tag{5}$$

or in terms of Eq. (4) as

$$\begin{aligned} C &= \alpha(1+D)(R-T)\Gamma + \beta T \\ &= \alpha(1+D)R\Gamma + [\beta-\alpha(1+D)\Gamma]T. \end{aligned} \tag{6}$$

The effective cost of a terminal interceptor is $\beta-\alpha(1+D)\Gamma$. If that is less than zero terminal defenses are preferred; if it is positive, midcourse interceptors should be used instead.[5] Current interceptor costs, $\Gamma \approx 0.3$, and $D \approx 10$ give $\beta-\alpha(1+D)\Gamma \approx \$7M - \$2M \cdot 10 \cdot 0.3 \approx \$7M - \$6M \approx \$1M$. Thus, by the criteria above, terminal interceptors should not be used. Of course the effective cost of replacing midcourse with terminal interceptors is small, so if they were available they wouldn't hurt; they just wouldn't help much either.

The criteria for deploying the defenses at all is that they be cheaper than the $\approx \$20M$ cost per RV to the offense, or $C/R < \$20M$. For current costs, by Eq. (6) that essentially requires $\alpha(1+D)\Gamma < \$20M$, or $D < \$20M/\alpha\Gamma \approx 30$ decoys per RV.

E. Breakeven

The break-point between midcourse and terminal interceptors occurs at about $D \approx \beta/\alpha\Gamma - 1 \approx 10$ decoys, which is about where the whole defense breaks down. The 10 + 1 midcourse interceptors would cost about \$22M, which is more than the ≈ \$20M cost of an RV from a heavy missile. However, their preferentiality reduces their effective cost by a factor of Γ, which extends their usefulness out to about 30 decoys. Thus, terminal defenses compete only in the region where midcourse--and whole defense--are marginal and leave little resources for the boost-phase defenses required to reduce current threats to manageable levels.

The upper end of the decoys deployed, $D \approx 20$, gives an effective cost of $\beta - \alpha(1+D)\Gamma \approx -\$5M$, so terminal defenses would be effective. The offense could, however, attack them preferentially. For $T/N \approx 1$, about all the shots realistically permitted by the atmospheric battlespace, that would give about R/2 to N targets. The attacker's expenditure would be ≈ \$20M·R.

The terminal interceptors would have to defend all of the targets for a cost of ≈ \$7M·N. The cost effectiveness of the defense would thus be ≈ \$20M·R:\$7M·N ≈ 3R/N. If the attacker wishes to kill about $1-\Gamma \approx 2/3$ of the targets, that requires about $K \approx R/2 \approx 2N/3$ kills, or $R \approx 4N/3$ weapons. Thus, the exchange ratio would be about $3R/N \approx 4$. If so, the terminal layer could be quite effective.

III. LIMITATIONS

There are practical reductions in effectiveness. Kill probabilities of terminal interceptors could be limited by footprints, fratricide, and guidance to 0.7-0.8.[6] In that case, for the defense of high value targets such as air bases it would be appropriate to launch more than one terminal interceptor at each target. Given the short time lines it would probably not be possible to shoot-look-shoot, so it would be necessary to volley two interceptors at each target. That would give compound kill probabilities of 90-95% and still maintain a cost effectiveness of about 2:1.

The main limitation is battlespace. If sensors and interceptors can tolerate at most one salvage burst along a trajectory, then two weapons can kill any target. Cost effectiveness has three components: cost effectiveness relative to alternative defenses, the attacking weapon, and the target.

It is shown above that terminal interceptors are cost effective relative to midcourse for many decoys, and that they are cost effective relative to the threat for a single weapon per target, but they cannot defend against much more. Thus, if the attacker delivered two or more weapons, the target would surely be destroyed. In that case the relevant ratio is the defense's loss to the offense's expense.[7] For a weapon attacking a multi-billion dollar air base, the ratio could be $\approx$ 100:1 in favor of the offense. Terminal defenses are good for about one round, quite effective if the attack can be held to that, and irrelevant otherwise.

IV. INTEGRATION

Thus, the strengths and weaknesses of midcourse and terminal defenses are largely complementary. Midcourse interceptors can handle large numbers of weapons at relatively constant cost effectiveness but could be compromised by many decoys. Terminal interceptors can handle few weapons per target but could do so relatively effectively. Thus, the criteria for their inclusion are driven by economics and decoys.

A. Midcourse and Terminal

For current costs, terminal interceptors would not be used, but for slightly higher midcourse interceptors costs they would be. They would be added as essentially a one interceptor layer, and the remaining attrition needed would be built up from mid-course interceptors. The cost of the composite would be given by Eq. (6). If terminal and midcourse costs were comparable the cost per RV engaged would be about $C/R \approx \alpha(1+D)\Gamma$. If that cost was less than the \$20M per RV, the composite would be deployed; otherwise not. The criteria is roughly $D < \$20M/\alpha\Gamma \approx 30$ decoys.

B. Terminal and Boost Phase

Boost-phase and terminal defenses can also be integrated. There are conditions under which the two could suffice; unfortunately, they are not current conditions. Currently the Soviet Union has about 1,000 modern intercontinental ballistic missiles (ICBMs) with an average of ≈ 10 RVs each. They would attack about 1,000 missiles and another 1,000-2,000 military targets, so there would be about 3-5 RVs per target.[8]

If the targets had only terminal defenses, they would saturate, and nothing would survive. START could reduce the number of ICBMs to about 3,000, but submarine-launched ballistic missiles (SLBMs) would still bring the total up to about 4,500. Against 2,000 targets there would be more than 2 RVs per target, and terminal defenses would still saturate--though by a smaller margin. Thus, a factor of 2 or so attrition in boost might make terminal defenses viable. That seems possible, even in the near term.

There is a simple analytic function for the number of RVs penetrating the boost phase[9]

$$R \approx mM \cdot e^{-fK/M} + M_1, \qquad (7)$$

where m is the initial number of RVs per missile, M is the number of heavy ICBMs launched, K is the number of boost-phase space-based interceptors (SBIs) deployed, and f is the fraction of the SBIs within range of the launch, which is about 0.13 for heavy missiles in the near term.[10] The number of mobile singlets, M_1, is essentially unattrited by near-term constellations.[11] The fraction of RVs penetrating from Eq. (7) is exact for both small and large K, but is only approximate at intermediate constellation sizes.[12] The main discrepancy is near $K \approx M/f$, where the exact result gives 10-20% more kills than the approximation. It would at worst halve the demands on the midcourse and terminal layers.

SLBMs are dominant at small K, but strongly suppressed by $K \approx 1{,}000\text{-}2{,}000$. Each submarine represents a small point launch; constellations sized for the much larger ICBM launches are oversized for SLBM launches.[13] For that reason they are ignored in

the analytic discussion below. It is later shown that the omission is only significant for START forces and many targets. Fluctuations are also ignored. Random removal of missiles in the boost phase would cause some silos to receive no RVs, some to receive more than one. For this small a number the fluctuations are modest and are ignored below.[14]

For N targets, the boost phase would have to attrit the 270 x 10 heavy plus 340 singlets ≈ 3,000 ICBM RVs down to no more than one per target for the terminal defenses to handle the rest. The needed attrition is not great. For 2,000 targets there would be only about 1.5 RVs per target to start with. If about 0.5 RVs per target, or 1,000 RVs, could be destroyed, all targets could survive a uniform attack.

Of course, the attack would not be uniform. The attacker would concentrate his attack in order to meet his goal of destroying roughly $1 - \Gamma \approx 2/3$ of the targets. According to Eq. (2), for one terminal defense per target that would take a reduction to about $K \approx 2N/3 \approx R/2$, or $R \approx 4N/3 \approx 2{,}670$ weapons. Inverting Eq. (7) gives

$$K \approx (M/f)\ln[mM/(R-M_1)] \approx (270/0.13)\ln[2{,}700/(2{,}670-340)] \approx 2{,}080 \cdot 0.15 \approx 300, \quad (8)$$

which indicates that a very small constellation could apparently reduce the number of penetrating RVs to the point where the attacker could not effect damage limiting from all U.S. ground-based forces. If the attacker tried to limit damage from missiles only, N = 1,000, that would give R = 1,333, for which $K \approx 2{,}000$, which is larger but still modest by current goals.

These estimates can be made more precise. SLBMs can be included by extending Eq. (7) to

$$R \approx mM \cdot e^{-fK/M} + M_1 + nH \cdot e^{-fK/\phi H}, \quad (9)$$

where $n \approx 6$ is the average number of RVs on each of the H SLBMs. The SLBMs and ICBMs have about the same booster burn and deployment times, so f is about the same for both. The factor ϕ is included to incorporate clustering before launch. Each submarine has about 20 missiles. If launched simultaneously against a constellation designed to attrit $M \approx 300$ ICBMs by about

a factor of $x = e^{-fK/M}$, a boatload of SLBMs would be attrited by a factor of $e^{-fK/20} = (e^{-fK/M})^{M/20} = x^{M/20}$. Thus, for a factor of two attrition of the ICBMs, individual SLBMs would be attrited by about a factor of $(1/2)^{M/20} \approx (1/2)^{300/20} \approx 3 \cdot 10^{-5}$.

SLBMs are strongly attrited by SBIs. Their best defense is to cluster before launch, which improves penetration. Since about half the boats are in each ocean and about half of each in port, about the best that can be done is to concentrate H/4 SLBMs in 4 locations: two ports and two rendezvous at sea. That corresponds to $\phi \approx 1/4$, and a launch of about $\phi H \approx 100$ SLBMs from each site. For an ICBM attrition of x, that would give about $x^{M/100} \approx (1/2)^3 \approx 0.125$ for the SLBMs. Thus, at interesting levels of defense the SLBMs would still be attrited by about an order of magnitude more than the ICBMs, but at least they could make some contribution. Since $mM \approx nH$, the SLBMs make a useful contribution only for $x \approx 1$.

With the above substitution for x, Eq. (9) becomes

$$R - M_1 \approx mM \cdot e^{-fK/M} + nH \cdot (e^{-fK/M})^{M/\phi H} = mMx + nHx^{M/\phi H}, \quad (10)$$

which is awkward to solve in general. For START forces, however, $M/\phi H \approx 300/0.25 \cdot 400 \approx 3$, so the equation is degenerates to a cubic, whose solution is $x = A + B$, where $A = (-b/2 + q)^{1/3}$, $B = -(b/2 + q)^{1/3}$, and $q = (b^2/4 + c^3/27)^{1/3}$. The solution for START forces is shown in Fig. 1. The bottom curve is the number of targets defended, which is equal to the number of terminal interceptors; the middle curve is the number of SBIs needed; and the top curve is their combined cost. K is about 8,000 at N = 300, but it drops to about the 4,000 of phase 1 by 500 targets. At N = 1,000, i.e., defense of missiles only, K drops to about 2,500; for missiles, air bases, and 1,000 other military targets it drops to about 1,000 SBIs, in agreement with the analytic estimate. The cost is in the range of $10B throughout, which is comparable to that for boost and midcourse, when effective.

Figure 2 shows the companion calculation for roughly current forces, i.e., 1,000 heavy missiles but with SLBMs adjusted to have the same $M/\phi H \approx 3$. The SBI curves are similar; the costs fall with N rather than rise; but the main difference is

magnitudes. For ≈ 1,000 targets about 15,000-20,000 SBIs would be required, which probably could not be deployed. Thus, as stated earlier, terminal defenses would probably not be useful against current forces.

Figure 3 shows the ICBM and SLBM penetration for START forces. For N ≈ 300 the boost phase must hold penetration to about 1% to meet the required number on target. By 1,000 targets the allowed penetration increases to about 40%; by 2,000 it is about 60%. SLBM penetration is negligible at the former and only about 20% at the latter. Figure 4 shows the penetrations for current forces. Boost phase increases almost linearly from ≈ 0.5% at 300 to 22% at 1,900. SLBM penetration is negligible everywhere. Large launches require very strong suppression.

Constellation sizes would grow over time due to modernization of the offensive missiles and compact basing, which could increase the absentee ratio 1/f about a factor of 3 in the midterm and another factor of 3-5 in the long term.[15] However, neither absentee ratio is prohibitive. The changes would merely rescale K in Fig. 1. Thus, it would appear that terminal defenses could be combined with modest boost-phase constellations to protect military targets. That approach would not, however, appear to extend to the coverage of cites. For only ≈ 300 major cities, even in the near term the R ≈ 4N/3 ≈ 400 weapons required would give K → 10,000, since almost that many weapons could be delivered by the current mobile missiles alone.

V. SUMMARY AND CONCLUSIONS

Midcourse interceptors could effectively engage bare RVs, but their effectiveness falls inversely with the number of decoys per RV and their cost reaches that of the offense at about 10-20 decoys per RV. Terminal interceptors exist and have advantages, such as the possibility of atmospheric discrimination, but also have disadvantages such as cost, saturation, and susceptibility to preferential attacks.

They would not be used for current costs but could be effective for slightly higher midcourse costs or decoys. The

criteria for shifting from midcourse to terminal interceptors is that the number of decoys per RV be about $D > \beta/\alpha\Gamma \approx 12$ for current costs and objectives, which is close to the $\approx \$20M/\alpha\Gamma \approx \$20M/\$2M \cdot 0.3 \approx 30$ decoys per RV at which the whole defense would lose effectiveness.

The main limitation on terminal interceptors is battlespace, which limits them to about one intercept over each target. Thus, if effective, they would be added as a one intercept layer, and the remaining attrition needed would be built up from midcourse interceptors. If their composite cost was less than the offense's, the layers would be deployed.

It is also possible to integrate boost and terminal phases. Simple approximations to the number of RVs penetrating boost indicate that it should be possible to reduce the attack to the ≈ 1 RV per target terminal defenses could handle. For attacks on both missiles and air bases the number of SBIs needed is in the hundreds; for attacks on missiles only it is in the thousands; for attacks on cities it is of course extremely large.

While terminal defenses are of little value by themselves, they would appear to be quite useful in conjunction with midcourse defenses, whose sensitivity to decoys they could offset, and with boost phase defenses, whose lack of preferentiality they could partially compensate for. Thus, they appear to provide a useful additional layer in defending military targets, although their role in defending cities is modest.

ACKNOWLEDGMENT

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Fig. 1 Terminal defense vs START

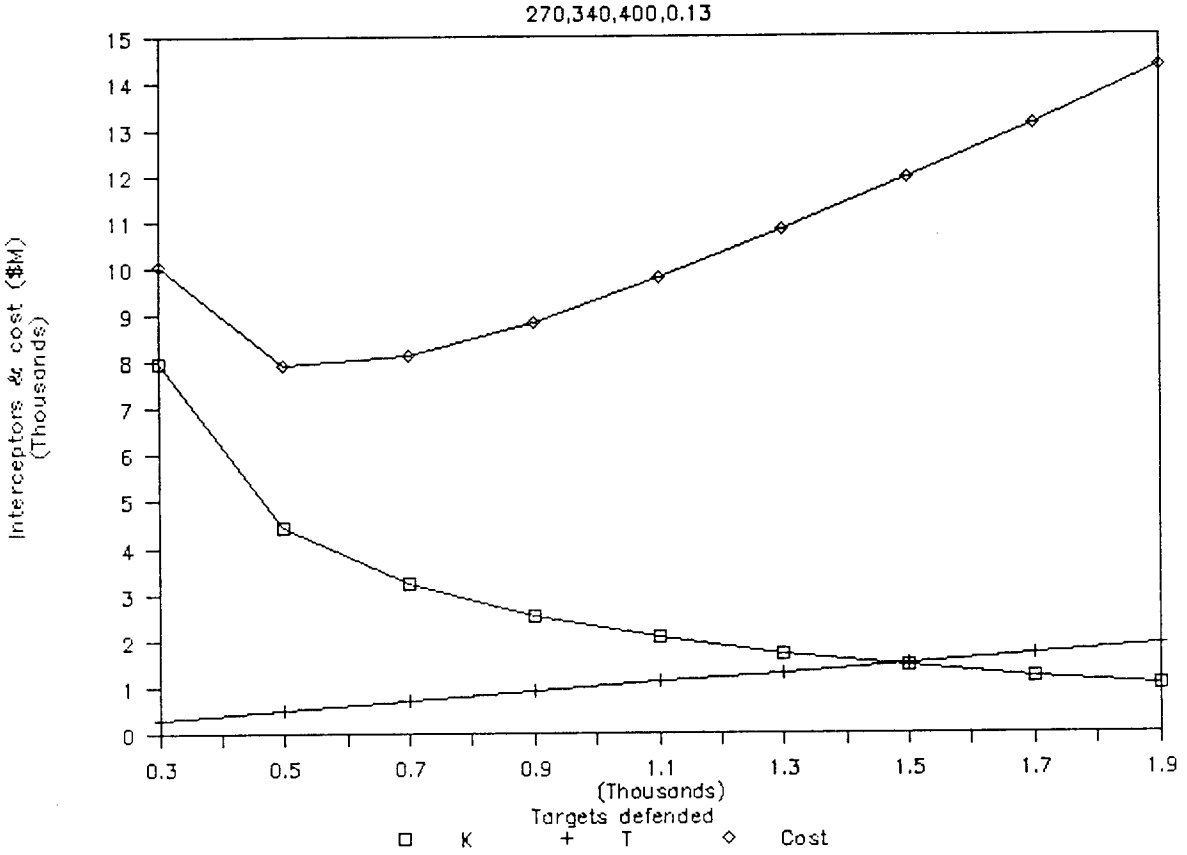


Fig. 2 Terminal defense vs current

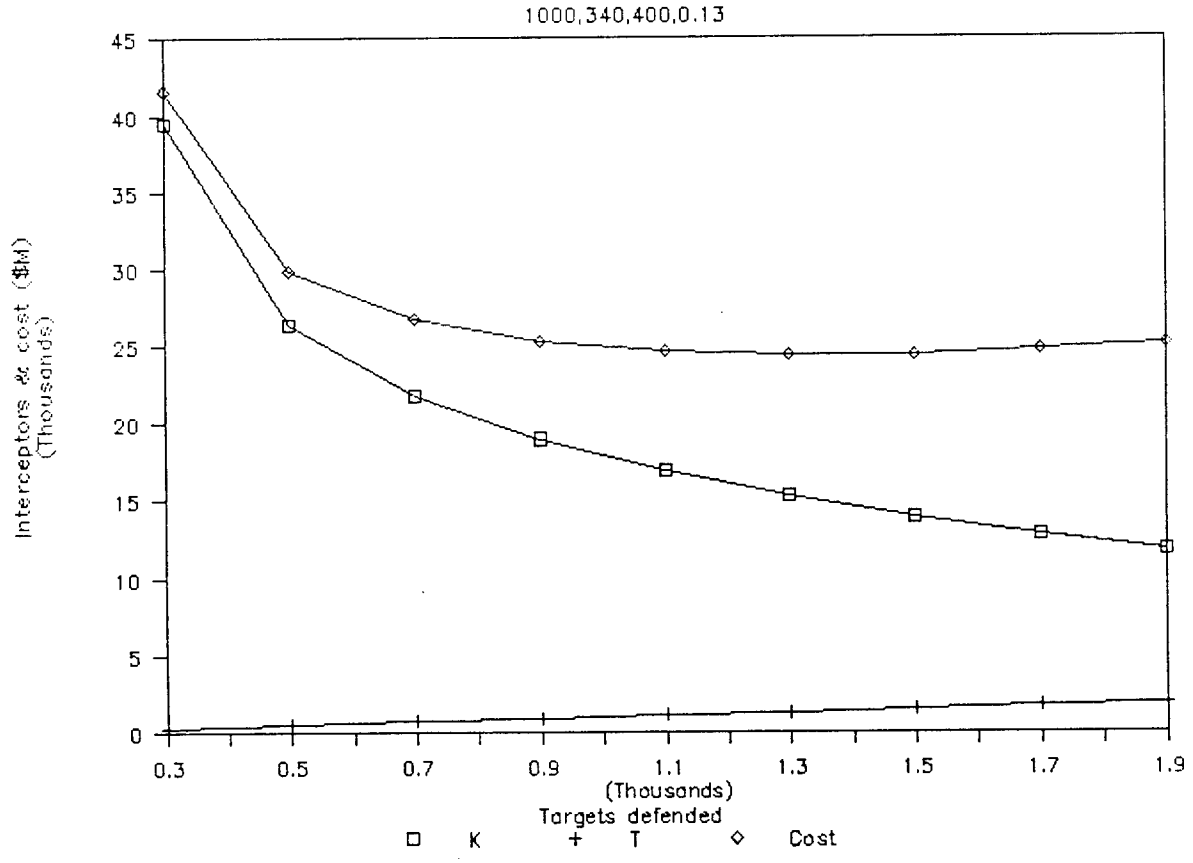


Fig. 3 Penetration of START

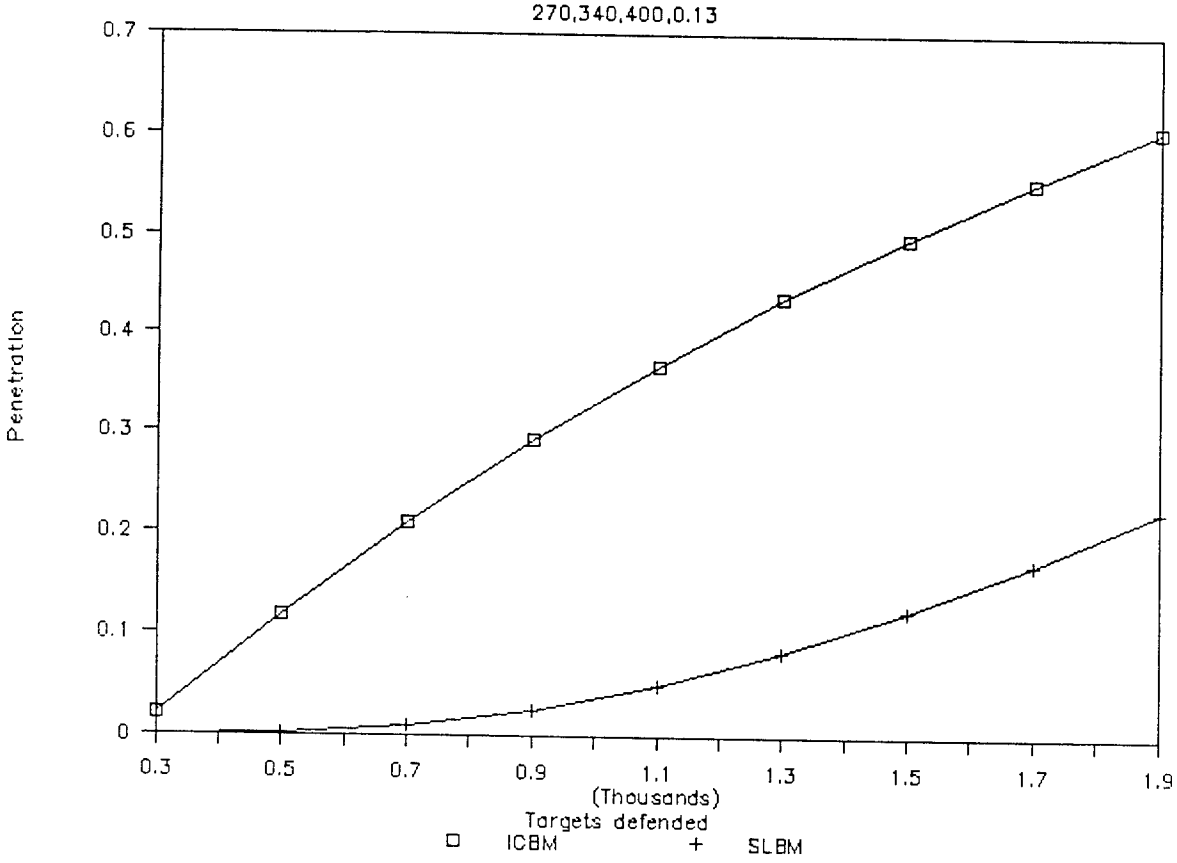
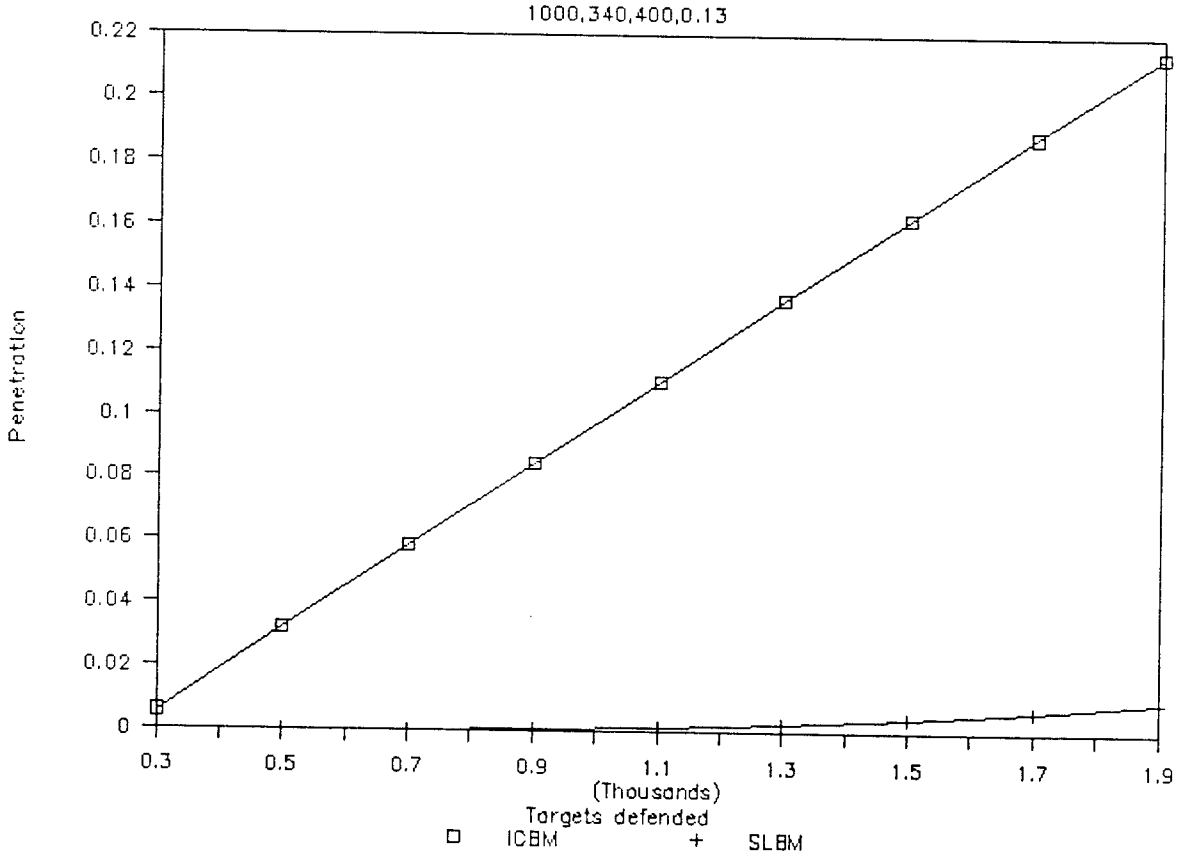


Fig. 4 Penetration of current



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