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DIRECTED ENERGY CONCEPTS FOR STRATEGIC DEFENSE

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by

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ABSTRACT

Directed energy concepts can play unique roles in strategic defense because of their reaction time, speed of light engagement, and large geographic coverage. This report discusses the main directed energy concepts, engagements in which they could have significant leverage, and their expected performance in them. It covers both boost phase engagements and midcourse applications, and contrasts these results with those of earlier analyses.

I. INTRODUCTION

This report discusses the directed energy concepts for strategic defense, describes the roles they might play, and assesses their likely effectiveness. This section describes the two defensive layers in which these concepts might play significant roles, either as sensors or interceptors. Section II discusses boost phase intercepts, where the main role could be in providing an adequate and robust kill rate. Also, Section II indicates the overall scaling of boost phase constellations, how each directed energy concept would contribute, and their main sensitivities and issues. Section III does the same for midcourse applications, where emphasis shifts to discriminating the numerous decoys possible. Section IV compares these results with previous analyses.

Section V summarizes the status of the results relative to the time scale on which their contribution might be necessitated by an evolving threat, concluding that directed energy concepts' performance, cost, and robustness could make them a useful supplement to kinetic energy in the mid term. The examples primarily treat large, simultaneous launches, which are the most stressing if not the most likely engagements. The limited launches and extended engagements of current concern are discussed elsewhere.[1]

The goals and technologies for strategic defense have been discussed extensively over the last few years,[2,3] and a recent report by the American Physical Society (APS Report) complemented those broader treatments with detailed discussions of the physics and expected performance of the the main directed energy weapon (DEW) concepts.[4] It is used below in the technical basis for a discussion of how those technologies could be integrated over time into the layered defenses required to meet those broad goals.

Such defenses break into three distinct layers: boost phase, midcourse, and terminal intercepts. In the boost phase there is a significant advantage in destroying the missiles before their reentry vehicles (RVs) and decoys are deployed. In midcourse all objects, including light decoys, follow ballistic trajectories, and the defense must be able to discriminate them to remain effective. And in the atmosphere decoys are slowed and discriminated by atmospheric drag during reentry. Because DEW concepts have difficulty in propagating through the atmosphere, the APS Report argues that they should have less application there, so the discussion below concentrates on the first two layers.

II. BOOST PHASE INTERCEPTS

In the boost phase it is possible to attack the offensive missiles and buses, which are generally more vulnerable and less numerous than the RVs and decoys they carry. The main boost phase concepts are kinetic energy interceptors,[5] space based lasers, ground based lasers, and particle beams.[6] The following paragraphs indicate their principles of operation, scaling, and countermeasures, starting with a brief sketch of the kinetic energy concepts with which they compete.

A. Kinetic Energy

Kinetic energy weapons (KEWs) destroy boosters and buses by colliding with them, which is essentially an extension of tactical missile technology to strategic engagements. The main advantages of KEWs are the modest size, cost, and complexity of their missiles and homing sensors and the difficulty of countermeasuring impact kill at the boosters' intercontinental velocities. Fast burn boosters are the main countermeasures to space based interceptors (SBIs) because they could significantly reduce the time available for the SBI to reach the launch area and might even be able to burn out at altitudes that were inaccessible to simple infrared (IR) homing sensors. Their impact is, however, compromised by their buses' need to drift through altitudes where the defensive missiles can intercept them in order to reach the altitudes needed to be able to deploy decoys without unmasking them.

If an object of ballistic coefficient β = mass per area is released at an angle θ above horizontal in air of density D, drag reduces its velocity by a fraction $r = DHC/\beta\sin\theta$ over roughly the next scale height, H, where the drag coefficient, C ,is about unity.[7] The value of r needed for discrimination is determined by the sensitivity of the sensors, which has been estimated as about 10 cm/s ÷ 10 km/s = 10^{-5}. For RVs with nominal ballistic coefficients of about 1000 kg/m^2, a 1% mass decoy would have

$\beta = 10\ kg/m^2$. That gives $D = r\beta\sin\theta/H = 2.4\cdot10^{-9}\ kg/m^3$, which corresponds to the altitudes cited in the APS Report, which concludes that if "the defense is given credit for acceleration measurements of $10^{-2}g$, the offense would need to delay deployment from the PBV [post boost vehicle or bus] until an altitude exceeding 120 km was reached," and that discriminating on velocity instead could force deployment up to about 150 km.[8]

Drifting to 120-150 km before deployment increases the boost phase engagement time from the tens of seconds of the fast booster's burn to 100 s or more, a dilation that is relatively insensitive to the missile's acceleration. The resulting engagement window of a few tens of seconds is adequate for SBIs because their engagements are near simultaneous, which has been conceded by earlier critics: "With respect to fast-burn boosters there indeed appears to be an altitude band between 100 and 120 kilometers in which the offense would have trouble and expense in deploying decoys and MIRVs. Thus KEWs could target MIRVed ballistic missiles there, depending on how much success the offense has in making such deployments near 100 km at acceptable penalty."[9] Since the bus from even a fast burn booster still has to drift up to these altitudes before starting deployment, it does not matter that much how far below them the booster burns out. The establishment of a lower limit of about 100 s to the engagement time is also a significant benefit to the directed energy concepts.

For any given launch parameters, the interceptors' velocity determines the optimal SBI constellation size, which can be determined analytically. In the near term a total of about 6,000 interceptors, each roughly as big and heavy as a man, would be required to engage the simultaneous launch of 1,400 missiles. If M missiles are launched from an area, A, and are vulnerable for a time, T, the areal density of interceptors needed is $N'' = M/\pi(W+vT)^2$, where v is the interceptors' velocity and $W = (A/\pi)^{1/2}$ is the effective radius of the launch area.

For current launch area of 10 $(\mathrm{Mm})^2$, time of 300 s, and optimal interceptor velocity of v = 6 km/s, which is about the largest practical with simple missiles, KEWs from an area about four times as large as A contribute. The total number of satellites in the constellation is $N = 4\pi R_E{}^2 N''/z$, where R_E is the earth's radius and $z \approx 3$ is the satellite concentration possible when coverage is concentrated on the missile launch area. Thus, $N = (4MR_E{}^2/z)/(W + vT)^2$. In the near term, the simultaneous launch of 1,400 missiles would require a total of about 6,000 interceptors, each roughly as big and heavy as a man.[10]

Space basing gives global coverage, but does so at the cost of absenteeism. Only the satellites within vT of the launch area can contribute to the engagement. A phase-space estimate of that fraction is $f = N''p(W + vT)^2/N = z[(W + vT)/2R_E]^2$. The constellation size scales as f^{-1}, often called the "absentee ratio." For A = 10 $(\mathrm{Mm})^2$, v = 6 km/s, and T = 300 s, f = 0.23. For current parameters, about 23% of the satellites would be available for boost phase engagements, but that fraction could decrease significantly over time. In the mid term a higher fraction of mobiles could be clustered before launch, and modifications could reduce the deployment time to about 200 s. The fraction available would then fall to about 11%. On a longer time scale fast missiles and buses could be fully clustered, which would reduce SBI availability to 5% or less.

As noted above, further reductions in the engagement time would be difficult. Further reductions in the launch area are theoretically possible. They also involve penalties, but they are often overlooked because most are not incurred in the boost phase itself. Mathematically, it is advantageous to concentrate launchers and try to punch a hole in the defensive constellation, but there are drawbacks downstream in terms of reduced flexibility of attack timing and increased vulnerability of the offensive missiles and weapons.

Simultaneous point launch onto anything but a crowded "point trajectory" would produce nonsimultaneous arrival at each target, relaxing the time lines for midcourse and endoatmospheric defenses. Simultaneous arrival would require nonsimultaneous launches, which would lengthen the boost phase engagement and increase the effectiveness of boost phase defenses. Point launch also increases the vulnerability of the launchers to pin down, which would become both more efficient and more plausible given the provocation of clustering. Point launch also concentrates the targets in space and time in a manner that would increase the effectiveness of standard weapons in kill and discrimination. Point launches that required simultaneity in both launch and arrival could be put at risk by a single standard weapon.

Fast, mobile missiles could generate significant economic pressures, which can be roughly estimated. Reviews of preliminary DoD cost figures give a nominal cost of about $ 6 M per SBI, of which about 25% is for the interceptor, and the rest is divided about equally among the carrier satellite, if needed, launch, and operations. Sensors and command are estimated to add $ 10-20 B.[11] If so, in the near term engaging every missile in a full launch would require about $ 6 M x 6,000 = $ 36 B, plus sensors and controls, which is large but still advantageous compared to the attacker's cost.

The attacker's cost is is $ 140-280 B for 1,400 missiles, based on the $ 100-200 M per missile derived from the roughly $ 2 B cost of a ballistic missile submarine divided by the 20 missiles it carries or the $ 200 M estimated for a deployed 10 RV MX missile.[12] Single warhead mobile missiles are projected to cost about $ 100 M per warhead. There are statements that small silo-based missiles could be deployed for $ 20-30 M, but neither the estimates nor the survivability of missiles so based have been addressed in detail.[13]

Simple countermeasures to SBIs have been proposed, but none appear to change this comparison strongly. Fast missiles and small launch areas, however, though neither simple nor cheap, might be able to. If interim offensive measures could reduce the fraction of SBIs available to 11%, the number of interceptors would roughly double and their cost would increase to \$ 70-80 B, which would approach that of the offense. If further reductions were possible, the SBIs could be placed at a cost disadvantage in the long term. That possibility, together with the fact that the directed energy concepts could have both lower costs and less sensitivity to the concentration of the launch region in space and time, appears to be the main reason for developing directed energy concepts for the boost phase: they could provide robust responses to the fundamental countermeasures to KEWs and do so on the time scale on which those countermeasures might emerge.

B. Directed Energy

The following paragraphs describe the main issues in the application of DEWs to the boost phase. The first section gives a review of boost phase scaling, which is similar for all the DEW concepts and which gives the framework for assessing their possible contributions and sensitivities. The differences that do exist between the scaling of the different concepts, which have caused some confusion in the past, are addressed explicitly in the following sections that describe the basic mechanisms of each concept. Those descriptions are followed by discussions of their common and specific countermeasures.

1. Scaling

An essential question in determining the effectiveness of DEWs in the boost phase is the number of defensive satellites needed to counter projected offensive threats. Such estimates can be made most accurately by computer simulations, but analytic solutions give greater insight into the results, indicate their sensitivity to parameter changes, and produce scaling results that others can check. The simplest scaling arguments use elementary relationships.

A laser is characterized by its brightness, B, which is the product of its power and the square of the ratio of its mirror's effective diameter to its wavelength. The "20-10" chemical lasers have a brightness of about 2×10^{20} W/sr. A laser of brightness B produces a flux B/r^2 at range r, so that targets at a range r = 1000 km hardened to a limiting fluence of $J = 200\ MJ/m^2$ would be destroyed in about $t = J/[B/r^2] = 200\ MJ/m^2 \div [2 \times 10^{20}\ W/sr/(10^6 m)^2] = 1$ s.

In a 100 s engagement, such a laser could destroy about 100 missiles, so about 10 lasers would have to be in range for the simultaneous launch of 1,000 fast missiles. The APS Report calculated that the satellites would need to be an order of magnitude brighter on the arbitrary assumption that a single laser had to produce the 0.1 s kill time, an unstated assumption that propagates through all brightness estimates in the Report. The APS's assumption would have a single laser kill all 1,000 missiles.[14] Early studies estimated lower kill rates because of an assumption that all engagements took place at the maximum range possible, an error that impacts kill rates quadratically.[15] The total constellation would have to be a factor of 5-10 larger to account for absenteeism, giving a total of 50-100 satellites.

Refining these estimates requires proper treatment of the interaction between the satellite and target distributions. Two useful limiting analytic estimates have been published. The first assumes that the missiles are launched from a large area and that only the satellites directly overhead respond. This "interior solution" is a reasonable approximation to the optimum defense against widely distributed launchers. For a launch from an area A of M missiles of hardness J that are vulnerable for a time T, low altitude satellites that can retarget rapidly require a constellation size $N = (8pR_E{}^4JM/z^2ABT)^{1/2}$, which scales as $M^{1/2}$, is under 100 satellites for nominal parameters, and increases less rapidly than the threat.

The interior solution varies with the main parameters in roughly the same manner as the general solution over a limited range that corresponds roughly to anticipated threats, and indicates the tradeoffs between brightness and cost.[16] The complementary "exterior solution, [for] point launches where only the satellites outside the launch area contribute, is $N = 4R_E^2JM/\{zBT\ln[1 + 2R_EH/(h^2 + SB/J)]\} \alpha\ JM/BT$, which is linear in M but only logarithmic in switch time, S, constellation altitude, h, and maximum range $H = (2R_Eh)^{1/2}$."[17]

Neither limit is completely appropriate for current threats. Launch areas are too small for the interior solution to apply to much better than factor of 2 accuracy, but they are large enough for the point launch solution to be in error by factors of 4 or more. Thus, the contributions from both the interior and exterior satellites must be integrated. The "combined solution" that does so produces a defensive potential that exceeds the sum of the interior and exterior contributions because it redirects each satellite's fire to cover the entire launch area optimally. It reduces to the limiting solutions under appropriate conditions and has quasi-analytic solutions for conditions of interest. Its constellations are about a factor of 2 smaller than the exterior solution; for nominal parameters about 50 satellites are needed for the simultaneous launch of an advanced threat. The combined solution uses the large numbers of satellites needed for large threats to to advantage, converting the sums for kill rates into a two-point boundary value problem. The largest uncertainties are boundary effects, which appear to be less than 12%.[18]

Figure 1 shows the constellation sizes as functions of threat size. The bottom curve is for the combined solution, the second is for the interior solution, and the third is for point launch, all evaluated for a stressing simultaneous launch of 1,400 missiles hardened to 200 MJ/m^2 and vulnerable for 100 s.[19] The lasers are 20 MW, the mirrors 10 m in diameter, and the retarget time is 0.1 s, which is consistent with defense goals.

The number of missiles is varied by an order of magnitude above and below the current value of 1400, for which point launch requires 205 satellites, the interior solution 91, and the combined solution 48, for a ratio of 4:2:1. For larger M the point launch diverges, but the interior solution approaches the combined.

Figure 1 also shows the results of other recent studies. The Union of Concerned Scientists (UCS) initially predicted 2400 satellites, which is off the figure, but a subsequent "Errata" corrects it for specialized coverage to 700 satellites.[20] The UCS's current prediction of 300 satellites is shown by the star. Although its derivation is described as correcting for finite launch areas and range averaging, which should make its assumptions the same as the combined solution, the 300 satellites is a factor of 6.3 times larger than the 48 from the combined solution.[21] UCS reports are not sufficiently detailed for a thorough analysis of the discrepancy, so there is no indication of how it might scale to larger threats.

One of the authors of the UCS reports performed a separate analysis that predicts 79 satellites for parameters close to nominal, and near-exact agreement with the interior solution for the same parameters.[22] That is not, however, an independent test since the two calculations used essentially the same equations. That is also true of the APS Report analysis, which reproduces the limiting solutions above and gives the corrections for the earth's curvature, which is small compared to the discrepancy between their early scaling and the combined solution.[23] For the UCS's conditions, an initial analysis by the Congressional Office of Technology Assessment (OTA) predicted 160 satellites for 1400 missiles hardened to 100 MJ/m^2 and accessible for 150 s. Since the OTA analysis is linear, scaling N on JM/T to UCS parameters gives the 480 satellites shown,[24] which is about 60% higher than the UCS's 300, and a factor of 10 higher than the combined solution.

Since the OTA's calculations were incorrectly linearized, the discrepancy grows at larger threat rates. The OTA calculation only added satellites near others already in orbit, which under the OTA's conditions was equivalent to increasing the satellites' brightness rather than their number. This constraint prevented the range between the satellites and their targets from decreasing as N increases, improperly linearizing the scaling of N on M. The OTA's final report replaced this analytical work with numerical calculations in accord with those used here.[25]

Other tests largely involved point launches. The Committee of Soviet Scientists in Defense of Peace Against the Threat of Nuclear War report repeated the algebraic errors of the first UCS report, which invalidated its quantitative predictions.[26] The revision doesn't even attempt to derive the constellation scaling;[27] it presents instead, without reference, internally inconsistent numerical values tied to the earlier report.[28] One detailed comparison of independent analytic and computer estimates led to 20-30% agreement, but the comparisons were for line sources of targets, which could be solved analytically to that accuracy with an extension of the point launch solution.[29] There have been no detailed comparisons for the current distributed launch areas.

The slopes of the curves are significant for scaling. For point launch, the slope is always unity. The interior solution scaling varies from $M^{0.55}$ at M = 500 to $M^{0.75}$ at M = 14,000. It is about $M^{0.6}$ at the current M = 1,400. The combined solution scales as $M^{0.72}$ near N = 1,400 missiles, since adding the linear external contribution reduces constellation sizes but strengthens its scaling on M. The average exchange ratio between missiles and satellites for point launch is 1400:200 = 7:1 for all M. For nominal conditions, the interior solution gives 1400:90 = 16:1, and the combined solution gives 1400:48 = 30:1. The marginal exchange ratio is larger than the average ratios by 40-70%.

The quantity of ultimate interest is the cost exchange ratio. Although the information needed for its evaluation is not available at DEW concept's current stage of development, rough comparisons can be made. As discussed earlier, survivable offensive missiles typically cost \$ 100-200 M; satellite costs are less certain. Satellites of the sizes assumed above might be built and operated for about \$ 400 M each, i.e., the \$ 200 M investment estimated for lasers of the size assumed, doubled to roughly account for launch, support, and life cycle operating costs.[30] If so, the average cost exchange ratio would be \$ 100-200 M/missile·1400 missiles ÷ (\$ 400 M/satellite·48 satellites) = 7-15:1 in favor of the defense. That ratio would scale up or down in proportion to the actual performance and costs of the offensive and defensive concepts, but either value gives both reasonable effectiveness and some margin for the countermeasures.

Figure 1 also indicates the sensitivity of constellation sizes to other parameters. The satellite concentration factor z enters only through zN, so the vertical axis can be interpreted as zN/3, which shows that the 10-20% uncertainties in z produce only like uncertainties in N. The engagement time enters only through M/T, so if N scales as $M^{0.7}$, it also scales as $T^{-0.7}$, which is significant, since real launches would probably take much longer times than those assumed above. The current 600 s deployment times would reduce constellation sizes by about a factor of 4. The variation of constellation size with altitude, which impacts both deployment and survivability, is small, since the combined constellations properly incorporate the additional satellites that come into view, offsetting their increased range. Constellation size is essentially constant up to altitudes of about 1,000 km, increasing slowly thereafter.[31]

Sensitivity to retarget time, S, is similarly suppressed by the larger fraction of the constellation active in any given engagement. As S increases from 0.1 to 1 s, 10 times the nominal retarget rate, the combined solution only increases in size by about a factor of 2.[32] The averaging of retarget angles has been a source of confusion in the estimation of retarget times. From a typical range of 1000 km, a launch field 100 km in diameter subtends an angle of about 100 km/1000 km = 0.1 radian. The field contains about 100 missiles whose average spacing is 100 km $\div (100)^{1/2}$ = 10 km, which gives a retarget angle of 10 mrad, and since the platform views the field at a slant, the required retarget angle is reduced to a few milliradians. For that it is not necessary to move the primary mirror; tilting a smaller mirror should suffice.[33] The APS Report omits these corrections, repeating the earlier, incorrect estimate that it would be necessary "to steer such large telescopes rapidly between targets with retargeting times of < 1 sec over angles that may be as large as 20 degrees."[34]

The strongest variation is that of constellation size with launch area, e.g., for compact launches. While point launch is independent of the launch area, A, the interior solution scales as $A^{-1/2}$ for large A and as A^{-1} for small A. Figure 2 shows that the combined solution varies as $A^{-0.3}$ for values of interest, so that its solutions are less sensitive to reductions in the launch area. The penalty for reducing the launch area all the way to a point would only be a factor of 4, which is much smaller than that for kinetic energy. The cost effectiveness would only be reduced to about 2-4:1 in favor of the defense by reducing the launch area and time to their minima. That would provide a factor of 4 or more advantage of DEW over KEW concepts under those extreme conditions.

A summary of this discussion of constellation scaling is that space laser platforms with performance within reach of that already demonstrated could provide a capable defense against a significantly advanced threat. Defensive constellations should not be overly sensitive to either their own performance parameters or those of the threat, which should enable them to retain effectiveness against anticipated variations in the threat. While cast in terms of space chemical lasers, these derivations and observations also apply to space and ground based free electron lasers, excimer lasers, neutral particle beams (NPBs), and directed nuclear concepts, because each can be characterized by a brightness, retarget time, and lethal fluence, which is the only information required for the analysis. The sections below identify the aspects of performance specific to different concepts.

2. Space Chemical Lasers

Space chemical lasers burn rocket fuels to produce power, which is focused with large mirrors on distant targets, where it can melt holes in hardened targets in a fraction of a second. The Defensive Technologies Study (DTS) assumed that laser powers of tens of megawatts and mirror diameters of tens of meters were attainable.[35] The summary of the APS Report states that chemical lasers "require power levels to be increased further by at least two orders of magnitude,"[36] but the body of the Report acknowledges that the "MIRACL (chemical laser) has produced...a measured power in excess of 1 MW."[37] Thus, the extrapolation to the nominal 20 MW lasers for the boost phase is only about one order of magnitude rather than two.

After its first laboratory demonstration the chemical laser was scaled to about 100 kW with good beam quality in less than 2 years; subsequent development has been paced by budget and mission conflicts. The missions studied spanned air combat, air defense, ship defense, ASAT, DSAT, and strategic defense. Each shift in mission caused shifts in both technology and design. Thus, the demonstrations of power, efficiency, size, and geometry have largely involved different devices in different facilities. There does not appear to be a technical barrier to demonstrating them together, just a lack of consensus and priority.

In the past the possibility of brightness degradation by vibrations from the combusting flow has been a concern for space based operation, but as the APS Report notes, the laser "burns smoothly...and the radial exhaust of the spent gases should also be relatively free of mechanical vibrations,"[38] which eliminates the major source of platform vibration, which, however, was still identified as a significant concern in the summary.[39] Many of these comments apply to other lasers that burn fuels to provide laser power in space. It is not clear that a chemical oxygen-iodine laser and generator would have much more than the factor of 2 advantage in mirror diameter over the high frequency (HF) chemical laser, and that would probably only amount to a few tens of a percent reduction in platform mass. Even if it were more efficient and operated at a shorter wavelength, the fuel for the IR chemical laser is already perhaps the cheapest part of the system. Visible chemical lasers might overcome this, but they don't exist.

3. Free Electron Lasers

Free electron lasers (FELs) produce high power laser beams from electron accelerators, which are developed and efficient. The main issue appears to be the efficiency of conversion from the electron beam to the laser beam. The APS Report's comments on these issues are detailed, but the main issues--operating FELs in the visible and scaling their injectors--have already been accomplished.[40] FELs could be sufficiently efficient and light to be deployed in space. If so, FELs with the brightness and retarget times used in the calculations in Section 1 would require the same constellation sizes as those shown in Figs. 1 and 2. For space basing, the FEL's advantages are its efficiency and short wavelength. The former means that less fuel would have to be expended per joule of laser light; the latter means that either its power or mirror diameter can be reduced significantly.

Chemical lasers in space have a specific energy of about 500 kJ/kg, so providing 20 MW of power for 100 s would require about 20 MW x 100 s ÷ 500 kJ/kg = 4 tonnes of fuel, plus some for reserve. The FEL could burn fuels with specific efficiencies of about 5 MJ/kg, about 10 times higher. If 30% of that energy was converted through electrical and into laser power, the fuel required to provide the same energy would drop to about 1 tonne, at which point the fuel cost and mass would be negligible. Alternatively, the larger fuel supply could be retained, in which case the the FEL could run much longer. If the fuel could be inserted into orbit for the estimated \$ 1 M/tonne, the \$ 1-4 M would be a small increment to the platform cost, in either case.

A laser's brightness is $B = PA/w^2$, where P is the laser's power, A the effective area of its transmitter, and w its wavelength. If the costs are linear, i.e., $C = pP + aA$, they are minimized by choosing $A = Pp/a$, which gives $P = w(Ba/p)^{1/2}$ and $A = w(Bp/a)^{1/2}$. For a given brightness the FEL's mirror diameter could be reduced by the ratio of the chemical laser's wavelength to that of the FEL, which is about 2.7 micron / 0.4 micron = 5.4, so the chemical laser's 10 m mirrors could be replaced by 2 m mirrors, reducing the mirror area about a factor of 36 and the cost potentially by a like amount. Alternatively, the FEL's power could be scaled down by $5.4^2 = 30$. In practice, both would be reduced in the manner that minimized cost. Since the brightness is trilinear in power, mirror area, and the reciprocal of the square of the wavelength, a simple optimization indicates that the power should be reduced by a factor of 5.4 and the mirror diameter by a factor of $5.4^{1/2} = 2.3$. Thus, a 4-4 FEL at 0.4 micron should have performance roughly equivalent to a 20-10 chemical laser at 2.7 micron.

Like the chemical laser, the FEL interacts with targets in an effectively continuous manner, so the two compete about equally on target lethality issues. Thus, the 4-4 FEL could kill a target hardened to the DTS limit in about 1 s. The fuel required to do so would be 4 MW x 1 s/(0.3 x 5 MJ/kg) = 2.7 kg. For each of the 10 lasers in position to kill 100 missiles, each would have to carry 0.3 tonnes of fuel. At a nominal 30% overall efficiency, the electrical power needed would be about 13 MW, which is within the capability of existing space generators.

Ground-basing of FELs is also possible because of their ability to generate high power beams for redirection by space missiles. In that mode, electrical efficiency and weight are less significant; the main issues are scaling and propagation. The constellation still involves 50-100 fighting mirrors, which engage the targets. If each FEL provides power for one fighting mirror, and the APS estimate of a factor of 4 transmission loss is used, the transmitted power from each FEL would be about 16 MW. The APS Report states that a ground based FEL "should produce an average power level of at least 1 GW,"[41] but that factor of 60 overestimate results from its incorrect scaling of the power needed from each laser and its implicit assumption that a single laser must engage the whole launch.

Propagation to space and back are also concerns. Uplink thermal blooming for (continuous wave) cw lasers is near-field, so it can be corrected completely, but turbulence produces phase distortions with a transverse scale r_0 that is 5-10 cm in the visible and near-infrared. These disturbances must be compensated dynamically. A transmitting mirror of diameter D requires about $(D/r_0)^2$ actuators, perhaps $(5\ m/\ 5\ cm)^2 = 10^4$, which is within an order of magnitude of current levels.

Producing that number of actuators could be done by replicating existing techniques, but they must also be controlled and the wavefront sensed at kilohertz rates. The references in the APS Report show, however, that the phase corrections are relatively local in configuration space, i.e., they strongly involve only the few closest neighbors, so that the computational problem of sensing and controlling grows as the number of actuators, $(D/r_0)^2$, rather than the total number of potential interactions, which grows as $(D/r_0)^4$. Thus, computation is largely a matter of replicating circuits; the control problem and rate required do not worsen with scale. Phase correction techniques appear to be somewhat ahead of where they need to be, given the 15-20 years until they are needed. Similar comments apply to the scaling of space elements. The downlink is more demanding. Ozone cannot limit engagements to 80 km because it is only present in concentrations that could produce blooming at about 30 km,[42] but Raman scattering could limit FEL downlinks, impacting the concepts differently.

4. Ground Based Lasers

A number of lasers can be based on the ground and used to provide power for redirection by mirrors in space, which can focus pulses of energy on targets, ablating material whose recoil punches holes in them in microseconds.[43] Short wavelengths minimize the sizes of the mirrors required. The main advantages of leaving the laser on the ground are that it can be built simply and that it and its fuel can remain on the ground, which minimizes the weight in orbit and makes the laser essentially inexhaustible. The disadvantage is that for boost phase engagements the power must be transmitted from where it is generated to the other side of the earth where the targets are. That requires that beams be transmitted up through the atmosphere and reflected by a mirror overhead to another "fighting" mirror over the launch area, for redirection to targets.

Uplink blooming[44] can be avoided by allowing the pulses to clear between pulses, and pulsed excimer lasers can synthesize a wide range of pulse lengths to avoid stimulated scattering, but the uplink still needs a cloud free line of sight. That would requires about a threefold redundancy in the absence of a cloud-clearing capability. The majority of clouds are thin, and hence might be cleared by modest adjunct lasers.

A 99.7% probability of a cloud-free line of sight can be achieved by increasing the number of widely dispersed sites by a factor of 5.[45] That multiplier drops significantly if it is possible to clear a hole in the clouds. Most clouds are thin, so the energy required is small. A cloud 1 km thick with 10^{-7} g/cm^2 of water could be penetrated with 10^{-7} g/cm^2 x 10^3 J/g x 10^5 cm = 10 J/cm^2, or 1 MJ for a 3 m uplink. Because the clouds are only a few km away, the clearing lasers would not need high quality optical beams. Thus, clouds could arguably be cleared with simpler lasers, built just for that task, colocated with the high power weapon lasers. The infrared lasers that appear appropriate could also be much less expensive than the discrimination lasers because of their higher efficiency and the reduced optical and pointing tolerances. The overall process, with spillage, might deliver only 20-30% of the transmitted power to the target, according to the APS Report.

Visible lasers of the same brightness as space chemical lasers would require the same size constellations of fighting mirrors, although they could produce that brightness with mirrors a factor of 5-10 smaller and hence 25-100 lighter. Since relay mirrors would need neither laser nor fuel, this large decrease in mirror size could be reflected directly in significant reductions in the platforms' mass and cost.

The APS Report states that "ground based excimer lasers for strategic defense applications must produce at least 100 MJ of energy in single pulse,"[46] but the vulnerability estimate gives pulsed kill at 5 kJ/cm^2 over 300 cm^2,[47] or 1.5 MJ delivered, which, with the APS estimate of a factor of 4 transmission loss, corresponds to 6 MJ transmitted. And the APS's 20 cm diameter spot is actually larger than the 10 cm spot that would be produced by a typical visible laser with a 5 m mirror from a typical range of 1,000 km. The demonstrated excimer pulse energy of over 10 kJ was from a prototype for 200 kJ modules. From it, the scaling required would amount to a factor of 6 MJ ÷ 0.2 MJ/module = 30 modules, whose output would be combined in Raman cells,[48] which has been demonstrated at scale according to the APS Report's references.

It is necessary to destroy about 1000 missiles ÷ 100 s = 10 missiles/s, but for nominal threats and laser brightness the engagement typically involves about 10 mirrors within range, so each could operate at 6 MJ/kill x 1 kill/s = 6 MW, rather than the APS's estimate of 1,000 MW,[49] which errors by a factor of 170 by assuming that a kill requires 100 MJ, which was discussed above, and that a single laser engages all targets. An excimer laser would thus require about 60 MW of electrical power, which could be tapped from existing capacity or generated with existing turbines. A FEL would require about 25 MW. Ground based assets have hardnesses greater than that of high value targets, so they could be defended, or defend themselves, sufficiently well to extract a commensurate price.

5. Particle Beams

Particle beams use the accelerators developed for high energy physics to produce high current, high energy beams of neutral hydrogen. Particle beams can disrupt or destroy electronics, detonate explosives, or weaken structural elements. This discussion applies only to beams of neutral hydrogen, which obey roughly the same scaling as lasers. Their lethality mechanisms, however, involve deposition in depth which can be significantly more effective. Particle beams can damage electronic components at depositions of 1-10 J/g and destroy essential warhead and structural components at 100-1000 J/g. The APS report uses 100 J/g for "massive upset," but that value actually corresponds to the melting of weapon components or the detonation of high explosives.[50] Upset can occur at as little as 10^{-5}-10^{-3} J/g. The APS beam lethality numbers were largely taken from the initial OTA report,[51] whose discrepancies were noted at the time.[52]

Existing structures might provide 10 g/cm^2 of shielding, so electronic components hardened to 10 J/g would require a fluence of about $J = 10\ g/cm^2 \times 10\ J/g = 100\ J/cm^2$ for lethality, about a factor of 200 lower than the fluence required for lasers. To penetrate a given areal density of shielding, $S(g/cm^2)$, the beam energy, $E(Mev)$, must be such that the particles can reach the vulnerable components. The penetration depth is $L(g/cm^2) = KE^{1.74}$, where $K = 3.3 \cdot 10^{-3} g/cm^{-2} Mev^{-1.74}$, so equating L to S to achieve penetration gives $E = (S/K)^{4/7}$. The APS Report observed that "lower particle energies are somewhat more efficient from a lethality viewpoint,"[53] but it does little good to efficiently heat the outer layers of the target; E must be sufficient to penetrate the shielding, i.e., if specific energy H(J/g) is required for damage, the incident energy required is HL = HS. For similar times and ranges, particle beams could kill targets at the same rate as lasers 200 times brighter.

A beam with I = 0.1 Amp, E = 100 MeV, and divergence θ = 1 μradian would have a brightness of $B = IE/\theta^2 = 10^{19}$ W/sr. By irradiating a missile for 1 s, its 10 MW beam could deposit about 10 MJ/m^2, or 100 J/g, which far exceeds the lethal level for electronics and is into the range for structural and explosive materials' damage. A beam energy of 100 Mev would penetrate about 10 g/cm^2, so an incident fluence of 10 MJ/m^2 would give a deposition of 10^3 J/cm^2 / 10 g/cm^2 = 100 J/g. This current of 0.1 Amp for 1 s would deposit 0.1 coulomb. This IE = 10 MW particle beam would require an input of about 30-40 MWe, not the 1,000 MWe in the APS Report.[54] For the correct beam power of 10 MW, the rejected thermal power could be about 30 MW_t, which would require about a 30 MW_t / 450 MJ/ton = 0.067 ton/s flow of coolant. For a 100 s engagement that would only amount to 6.7 ton, which is not excessive.

Particle beams can penetrate down to altitudes of about 120 km, which would give them a useful window for engaging buses that have to rise higher than that before deploying decoys.[55] The early Soviet and UCS SDI reports erroneously concluded that neutral particle beams could not propagate below 200-300 km by adding the scattering cross section to that for ionization, which is the only significant loss mechanism above 80-90 km. For the proper cross section the stripping can be calculated analytically to determine the 120-130 km penetration, which holds for angles well off zenith. Current boosters burn for 200-300 s, and their buses act for a like amount of time. So, if particle beams were available in the near term, they could be quite effective. Fast burn boosters could, however, begin their deployment at much lower altitudes. For the APS's 150 km deployment altitude, velocity discrimination[56] would give an engagement time $T = (150 - 120\ \text{km})/(7\ \text{km/s} \times \sin [21^{\circ}]) = 12$ s, which is about an order-of-magnitude less than that for lasers, but still significant. During deployment, buses cannot afford any disruption of their electronics, which can now be accomplished with very little current. Thus, particle beams could use their large total current to disrupt many buses in parallel. Preventing the bus from deploying its RVs is equivalent to destroying it. The key parameter for boost phase scaling is B/JT. For particle beams, it would only be about 1% of that for 20-10 chemical lasers, so the particle beam constellation could be reduced by a factor of roughly $(100)^{0.7} = 25$. Even at the APS's 100 J/g level, particle beams platforms could negate the advanced threat with currents of only 0.01 Amp. Note that for 10 J/g electronics lethality, delivering the 100 $kJ/m^2 \times 1\ m^2$ needed to negate a typical target would take a 25 MW beam about 4 ms, so that even with retargeting there would be roughly enough time for the 10 platforms in view to engage 1000 missiles in the 10 s available.

The potential performance of particle beams thus appears to be adequate, and their deposition in depth has significant advantages against countermeasures, as is shown below. Their main issues are coverage, weight, and cost. The estimates above assumed that the buses could not operate until about 150 km. If that altitude is depressed, the engagement time is depressed as well. At 120 km, the particle beams could only engage the buses after they had started deployment, which yields only partial value. Thus, in the boost phase, particle beams would have the greatest impact if deployed early. Weight and cost, which are usually directly related, are also of concern. Building a particle beam platform using the well-developed technology of high energy physics could produce a weight of 100 tons or more, but technologies demonstrated in the laboratory have the potential to reduce that by an order of magnitude. If so, it would have a major impact on this technology's effectiveness and survivability.

There are a number of other scaling issues. The APS Report states that NPB "must be scaled up by two orders of magnitude in voltage and duty cycle with no increase in normalized beam emittance," but it elsewhere states that the "use of drift-tube linac as the major acceleration section (from 5 to 200 MeV) appears relatively straightforward."[57] Their status was summarized by the APS Report by saying that "there do not appear to be major physics issues associated with these accelerators; rather, the issues are more 'engineering' in nature."[58] There were questions about the possibility of producing the "necessary current levels (> 100 mA) [which] must be scaled up by two orders of magnitude in voltage and duty cycle with no increase in normalized emittance,"[59] but it has been reported elsewhere that "a continuous wave ion source that produces 50 percent more current than required and has already met our beam quality goals" has already been demonstrated and that a 5 MeV accelerator has demonstrated that "the full beam current can be produced and accelerated with no significant emittance growth [and] the remaining issues of scaling up from 5 MeV to higher energies is now a modest extrapolation of beam accelerator technology."[60]

6. Countermeasures

Countermeasures could largely determine the effectiveness of the DEW concepts; whether the required lasers, mirrors, and particle beams could be built has been challenged less than whether they would be cheaper to deploy or to counter. The major countermeasures, fast burn boosters, fast buses, and compact launch areas, which were discussed in the Scaling section, impact the various lasers and the particle beams in roughly the same manner, extracting a significant but acceptable penalty from each. This section covers countermeasures that are specific to the different concepts.

Laser countermeasures primarily involve hardening the missiles, spinning them, and decreasing their engagement volumes. Hardening is achieved by adding ablative materials to protect softer elements from the laser radiation. Practical schemes must add the material over the whole booster, whose area is about 1,000 times greater than that of the spot irradiated by the laser, leading to a competition between the laser's preferential attack and the ablator's 100-fold higher chemical efficiency. For beams that track the heated spot, spinning the booster only decreases the laser's tenfold net advantage by less than a factor of 2, so in the boost phase hardening against chemical lasers is intrinsically limited.

Current missiles are not intentionally shielded, so they have hardnesses on the order of a few kJ/cm^2. Since existing missiles also require much longer deployment times than those used for the scaling estimates above, their launch could be met by a constellation of a few tens of modest 5-4 chemical laser platforms. For distributed launches the constellations scale as $(JM/BAT)^X$, from Fig. 1, near nominal X = 0.6 for the interior solution and about 0.7 for the combined solution. Current missiles are an order of magnitude softer than the nominal value used above and they require about six times as long to deploy. That is partially offset by the 25-fold lower brightness of the 5-4 lasers, but the constellation's size would still be reduced by a factor of $(25/60)^{0.7} = 0.54$, so that about 25 of these 5-4 satellites would meet the current threat.

Small lasers would not, however, provide the margin needed against harder, faster, and more compact missiles, buses, and launch areas, so the "nominal" calculations above used the hardening thought to be limiting. Since hardening primarily involves the addition of mass, it might be thought that as much as desired could be added, but that is not the case for missiles that must deliver useful payloads to intercontinental ranges.

An example is given by the APS Report, which estimates the payload penalties for the uniform shielding of large liquid missiles. The APS Report presented the equations for an optimally staged, unshielded "nominal" SS-18, but then it stated that, "Rather than treating the general case explicitly which is algebraically tedious, it is convenient to consider the case where the ablative shield masses scale according to [the stage masses]. With the answer to this case in hand and the answer for second stage shielding alone one can readily calculate the payload reduction for any mix of first and second stage shielding."[61] The discussion below treats the general case, since its payload penalties differ from those of the APS Report by about a factor of 2, which is not unimportant.

The APS Report presents the ideal rocket equations for an optimally staged, unshielded "nominal" SS-18, but assumes without justification that the shielding mass for each stage is proportional to its unshielded mass. For the Report's optimized nominal SS-18, the first and second stage masses were 146.2 and 30.4 tonnes, which led to first and second stage hardening masses of 4.8 and 1 tonne, respectively, which resulted in a payload reduction of about 2 tonnes, which is about a third of the useful payload.[62] The APS Report shows the SS-18 to be about 32 m high. The first stage is 20 m long, the second 8 m, and the bus about 4 m. Since the diameter is constant, the areas are in the ratio 20:8:4 = 5:2:1, ignoring the additional hardening required for the top of the bus. Thus, the ratio of the first and upper stage areas is is about 5:3 = 1.7:1.

The Report's information on hardening does not, however, provide uniform protection for all stages. For hardening by the retrofit addition of ablator, as reported, the uniform hardening of all stages would require that material be added in proportion to their <u>areas</u> rather than their <u>masses</u>. The reported stage masses are in the ratio 146.2:30.4 = 4.8:1, but the stages' areas are only in the ratio 1.7:1, so that in the Report's prescription the first stage would be harder than the upper stages by a factor of about 4.8/1.7 = 2.9, which would leave the upper stages, the ones most susceptible to attack, relatively unhardened. For uniform hardening, it is necessary to shield the stages in proportion to their areas, which corrects the APS Report's mass allocation by shifting hardening mass from the first stage up to the second stage and the bus, further reducing the payload.

The modification of the equations for uniform hardening of all stages is straightforward (Appendix A). Figure 3 shows the resulting payload mass as a function of hardening mass. The top curve is the APS curve in which the hardening is added in proportion to mass; the lower one is for uniform hardening. The APS considered nominal hardening to be the retrofit addition of 6 tonnes of ablator, for which the payload reduction is about 1.8 tonnes. For the same total mass, uniform hardening would reduce the payload by about 3 tonnes.

The APS Report also provides a framework for assessing the impact of this difference. The APS Report assumes that the unshielded PBV has ten 300 kg RVs, 3 tonnes of fuel, and 2 tonnes of structure--it actually gives 1 tonne for structure, but the total would then be 1 tonne short and the structure rather light.[63] In the APS Report's example advanced booster, the bus provides about 10% of the axial velocity, which means that if its fuel is removed for hardening, so are its range and possible missions. Short of bus redesign, every 300-600 kg reduction in payload reduces the number of RVs by one, with the lower mass corresponding to the elimination of RVs only and the larger mass to the offloading of a corresponding amount of fuel as well with each, which limits the missions possible with those remaining. For the latter case the APS Report estimated a net reduction of three RVs; for the former the reduction would be six RVs, which are 30 and 60% of the total weapons carried, respectively. For uniform hardening the reduction is about 3 tonnes, which would require the removal of 5 to 10 RVs, depending on the allowable mission degradation. Using small individual buses for each RV has been suggested as a counter to boost phase defenses, but since such a bus's mass could approach that of the RV, the scaling for individual buses should be about the same as that for large buses when RVs and fuel are offloaded together.

The payload penalty increases approximately linearly if more mass is required to achieve the needed hardening. If the required ablator thickness was doubled, giving a total hardening mass of 12 tonnes, for uniform hardening all the RVs and fuel would have to be removed from the current buses, although the useful payload of about 2 tonnes would presumably be used instead for about 2,000 kg ÷ 600 kg/RV = 3 RVs with individual buses, which would correspond to a 70% reduction of the threat. Further hardening would remove RVs proportionally. These results are consistent with the results of more detailed calculations given the results of analyses by Martin Marietta, which differ little for uniform shielding from the approximate calculation in Fig. 3. For 6 tonnes of hardening Fig. 1 gives a 2.8 tonne reduction in payload, for which the Martin Marietta curve for shielding both stages gives a 2.7 tonne reduction.[64] Thus, there is little disagreement in calculating the payload reduction, although there are uncertainties in whether that payload reduction should be taken in RV or mission reductions.

There are also idealized discussions of the shielding of only the first stage, the second, the bus, or combinations of them.[65] Comparisons of consistent configurations give results in agreement with those presented here, by Martin Marietta, and earlier studies.[66] Shielding only the first stage essentially corresponds to the case inadvertently treated in the APS Report, which would not be acceptable in practice. Hardening only the second stage has also been discussed, but cannot be justified operationally.

Since lasers can deliver the required energies down to the cloud tops, leaving the first stage unhardened would gratuitously reduce the defensive requirements for boost phase effectiveness by about an order of magnitude. Other types of missiles can be treated with more stages, solid engines, etc. The use of more stages could decrease sensitivity to hardening mass, but the solids' lower exhaust velocities increase it. Their net sensitivity could be greater than that evaluated above, but since such designs are more dependent on engineering details than the SS-18s discussed by the APS, it is less useful to present purely theoretical analyses of their payload sensitivity.

The uniform hardening of all stages requires about twice the payload penalties of the mass weighted hardening in the APS Report, which essentially hardened the first stage only. The payload penalties for hardening all stages could amount to a significant fraction of the RVs carried for nominal hardnesses, with the number of RVs removed varying from 5 to 10, depending on the mission constraints accepted. If greater than nominal hardening was required, uniform protection of all stages could leave little useful payload with existing bus designs and require the introduction of a significantly reduced number of RVs with individual buses. The reductions are sufficiently great that the missiles in the nominal calculations above should probably be regarded as carrying only 30-50% of the current number of RVs. While the analysis was couched in terms of space chemical lasers, it applies with minor modifications to the space or ground based FELs or excimer lasers as well.

A related countermeasure that has an impact similar to retrofit hardening is spinning the booster around its vertical axis to continually bring new shielding material under the laser beam. The Scaling section showed that, even for large hardening, the kill times were on the order of a second or less. Thus, for beams that can track the irradiated spot, the missile would have to rotate at least once per per second to have any impact. That would not be a practical retrofit to existing missiles. Even for a non-tracking beam the 3 m diameter SS-18 would have to rotate at over 20 rpm to increase the laser requirements significantly.

If the booster has radius r and rotates at angular velocity w and the laser spot has diameter d_S, material will remain in the beam for a time d_S/wr. For that to be less than the time, t, the laser takes to deliver a lethal fluence requires that $w > d_S/rt$. For the APS's SS-18 with $r = 1.5$ m, $d_S = 1$ m and a nominal $t = 0.3$ s gives $w > 2.2$ rad/s, which is over 20 rpm. RVs from PBVs rotating at such rates would miss their targets altogether. Since additional tolerance to stress is more difficult to retrofit than additional hardness, the latter approach would appear to be preferred.

The APS Report's discussion of depressed trajectories states that they "increase the time a missile spends within the atmosphere and is therefore unreachable by weapons for which the atmosphere is opaque,"[67] which applies to some concepts. For lasers, however, the effect of depressed trajectories is to increase the boost phase engagement time by a factor of 2-4, and hence decrease the defensive constellations needed by 30-50%.

Particle beam countermeasures are more difficult, since stopping a 250 MeV beam requires about 4 cm of lead, or 440 kg/m^2 of shielding, which is 10-100 times the hardening penalty for lasers. For a bus with an area of 10 m^2, shielding the entire surface to that level would take its whole payload; shielding just the critical components inside could involve a penalty of 2-4 tons. And unlike the earlier calculation for lasers, that penalty comes directly out of the useful payload. The hardening process is interactive, since if the offense shielded further, the defense could increase the beam voltage to overcome it. At 400 MeV, the beam could penetrate about 110 g/cm^2. Thus, by increasing the accelerator's efficient high energy sections by about 60%, the defense could increase the offense's shielding mass penalty by more than a factor of 10. The power and energy required to do so are modest.

The power and energy required to negate components shielded by an areal mass density L increase as $P = IE/(\theta R)^2 L$, where R is the range and θ is the beam divergence. Since θ scales as $E^{-1/2}$, P/I scales as E^2/L, or $E^{1/4}$, which by the earlier discussion is simply $S^{1/7}$, which is relatively insensitive to the shielding, S. Spinning the bus increases that penalty, because it exposes more area that must also be shielded.

The strongest potential counter to the NPB is the fast burn booster, since it ideally could burn out as low as 70-80 km, while particle beams only penetrate to 120-130 km. But if their buses must pass through altitudes the beams can reach to achieve the altitudes where they can deploy their payloads without loss of deception, the NPB can engage them in transit effectively.

Survivability of DEW platforms is a concern because of their size and relatively low altitude of operation, but it has been argued that even KEW platforms could use a combination of hardening, maneuver, and self-defense to survive in still lower orbits.[68] Compared to the KEW, the DEW platforms have a significant advantage in that their beams can be used not only in self-defense, but also to interrogate approaching objects. The most stressing threat for the defense appears to be direct ascent nuclear armed missiles that can dispense many decoys, which removes the KEW platforms' intrinsic advantages and converts the attack into a miniature version of the midcourse engagement. But the DEW's ability to discriminate restores such engagements to effectively one-on-one interactions that are favorable to the defender, even with platforms of significant size.

A variant of this analysis is the space mine, which is essentially only a very slow co-orbital attacker. In space such objects should not be difficult to detect, nor should they be difficult to interrogate once detected. The principal problem is assuring that the DEW platform's energy budget is such that it can afford to execute the few maneuvers per year that could be needed to avoid other satellites' keepout zones and that its defenses are such that it has the means to negate intruders that persisted in violating its own keepout zones and the endurance needed to await authorization to do so.

7. Summary of Boost Phase

The boost phase is an essential component of any defense intended to provide high attrition of the threat. In it, the targets are the missiles and buses with their RVs and decoys still undeployed, which makes it possible to significantly reduce the numbers of both reaching the other defensive layers, and with that the possibility of the saturation of downstream layers. In the boost phase both the offense and the defense have significant opportunities and difficulties. For the offense, the principal opportunity appears to be the development of affordable, mobile boosters and buses that can operate very rapidly in an attempt to minimize the engagement opportunity for KEW and to a lesser extent DEW platforms. The various forms of hardening offensive missiles are useful, but less powerful tools. The disadvantages to the offense are the expense and difficulty involved in developing these tools, whose costs could easily grow to a point where they would attrit the threat more than the defenses did. The challenges involved in developing hardened fast burn boosters that retain useful payloads, whole new concepts in buses, and mobile or survivable clustered launchers are not necessarily less stressing than those involved in the development of the defenses to meet them.

The main defensive opportunity is the possibility of developing various DEW concepts that could largely overcome the growing sensitivities of earlier KEW deployments and provide additional cost margin. The difficulty is that each requires as much as an order of magnitude further development. While there is enough time for that development before any actual deployment would be needed, there is little slack in development schedules.

The APS Report's summary statement that it "finds significant gaps in the scientific and engineering understanding of many issues"[69] is consistent with the expected status of a group of technologies that are neither expected nor required to contribute for the next 10-20 years, which should provide the "decade or more of intensive research [which] would be required to provide the technical knowledge needed for an informed decision about the potential effectiveness and survivability of directed energy weapon systems."

The study goes on to say, however, that all DEWs and "space power, beam control and delivery, sensing tracking, and discrimination" need "two or more orders of magnitude improvement," which manifestly cannot be justified on the basis of the material in the Report. The statements that chemical lasers, "because of their long wavelengths and other technical features...are perceived to be less attractive candidates for BMD" while "free electron lasers and excimer lasers are currently perceived as more attractive for BMD missions" could prove to be correct, but are not supported by any analysis in the Report. Space power requirements are trivial for housekeeping and within the range of already-developed technologies for burst power; the emphasis on this area apparently came from the factor of 10-100 overestimates of power requirements for the FEL and particle beam, since chemical laser and sensor satellites require little more power than the few kW supplied by solar arrays for existing satellites. The exception might be the APS's posited space radar, but its power is for mission, not housekeeping, activities. Survivability is an area of concern, although current assessments indicate that developed techniques should be adequate in the near term and DEW platforms should increase survivability in the long term. Overall, DEW concepts appear to have adequate potential margin relative to the offense, and their timelines for development are credible, if somewhat taut in places.

III. MIDCOURSE CONCEPTS

The midcourse is an important engagement region, if for no other reason than that it contains all but about 100 s, i.e., 95%, of the threat object's trajectory. This expanded engagement time is, however, accompanied by significant complications. The principal one is the large number of decoys that can be used there; the second is the sensor and processing problems they create. The two problems are related. If it was not possible to discriminate to a useful degree, the continued observation of the many objects passing, real and decoys, would not only be pointless, but it might also drive the bookkeeping up unacceptably, as commented on in the literature. If, however, it is possible to bulk filter the threat and then discriminate the remainder down to a few times the 1,000 or so RVs that might penetrate the boost phase in a large attack, then the processing problem associated with maintaining tracks on each object until it is engaged becomes commensurate with the processing problems encountered in earlier defensive systems.

A. Discrimination

Perhaps the most difficult aspect of developing an effective concept for midcourse is the discrimination of the numerous light decoys that could be deployed for a modest penalty in payload mass. That is not to say that the Soviets would try to defeat a U.S. strategic defense on decoys alone. There is no evidence that a leadership and military as conservative as those of the Soviet Union would put its survival into the hands of a few techniques for deception that never had been, and never could be, tested against our uncertain and possibly unknown discriminants and countermeasures, no matter how little payload those decoys might displace. Instead, decoys should probably be viewed is an adjunct that the Soviets would use in addition to the positive measures discussed earlier, although they still have to be treated properly.

A useful concept in evaluating the value of discrimination is the concept of the value of the object to be discriminated. A typical RV has a mass of about 300 kg and a value of about \$ 20 M [= \$ 140 M/missile ÷ 7 RV/missile(avg.)]. Decoys with a fraction of that mass could be used to conceal the RV by removing a lesser number of decoys. For a midcourse concept to be effective, the cost for it to discriminate and intercept the RV must be less than the value of the RV itself. This criteria of cost effectiveness at the margin would make it irrational for the adversary to proliferate the threat, although it is not, of course, the dominant consideration in treating less than all-out attacks. The discrimination and intercept concepts are discussed in turn below.

In space all objects follow ballistic trajectories, even the light "traffic" decoys, which are deployed in bulk not to confuse the defense's precision discriminators but to saturate its data handling capability. These decoys could be generated by destroying empty booster tanks; producing just 1,000 objects per missile by fragmenting the spent stages in a large attack could generate about 100 times as many "traffic" decoys as RVs. Not all would be credible. They might be too large, too small, or have unlikely combinations of emissivity and area. The defense clearly needs a bulk filter against such numerous but unlikely objects. For that purpose, passive inspection and low power microwave or laser imaging might suffice.

Even if bulk filtering is possible, however, the offense could also use decoys such as light balloons closely resembling RVs to bulk filters, allowing the RVs could to conceal themselves and consume still more of the engagement time. If the decoys had masses of about 10% of the RVs, or 30 kg, there would be about 10 decoys per RV. If it is assumed that that there are roughly equal cost and mass budgets for the discriminator and the interceptor, discrimination would have to cost less than about 0.5 x 2 x \$ 20 M/RV / 11 objects = \$ 1.8 M/object, where the 0.5 comes from the equal allocation of discrimination and intercept costs, and the factor of 2 comes from the half of the RVs that would have to be offloaded to accommodate the decoys. Acceptable discrimination costs would decrease with the mass of the decoys; they could credibly extend down to 1% of the RV, although decoys that light might be bulk filtered. The allowable cost for intercept would remain at about \$ 20 M, which is also a stringent target, as discussed in the next section.

Discrimination can be classified as either passive or active. The former includes concepts such as imaging and radiometric systems; the latter includes those from low power inspection to high power interrogation. Passive and low power techniques should suffice against the penetration aids initially encountered, and could be retained as effective bulk filters against larger threats for the longer term. But if time and development could produce decoys that looked much like RVs--and vice versa--to passive and low power techniques, then interactive measures would be required. Current candidates include pulsed lasers and particle beams, each of which uses known mechanisms to probe remote objects and infer their masses.

1. Laser Discrimination

When lasers deliver intense pulses of energy to objects, material is blown off whose recoil imparts a measurable velocity to the objects. The ratio of the impulse delivered to the velocity measured indicates the object's mass. If it is significant, the object is almost certainly an RV. The sensors to measure this velocity change exist, although the lasers required to produce it would require development.[70] The appropriate wavelengths for impulsive interrogation are in the visible and shorter. A megajoule pulse of visible light could impart a velocity of about 0.3 m/s to a 300 kg weapon or 30 m/s to a decoy with a mass only 1% as large. These estimates depend directly on the coefficient for coupling the laser light into impulse. The impulse data in the APS Report (p. 293) indicate that coupling can approach 10 dyne-s/J for fluences of interest, particularly on ablative materials. The effect of coating countermeasures is not known. Measurements on aluminum samples with microsecond pulses have given similar couplings, but the energies have been too small for directly scaleable experiments. Both velocities are readily detectable; their difference should be a robust discriminant.

Impulsive interrogation also usefully deflects objects. If the impulse was applied early in a 10,000 km trajectory, it would deflect an RV by about 0.3 m/s x 2,000 s = 0.6 km, which is larger than its kill radius against many targets; a 1% decoy could be displaced 60 km, which would clear the decoys from an area the size of a missile field. The deflection increases with the laser's energy and the reciprocal of the object's mass. Thus, midcourse lasers could not only discriminate RVs but also negate their hard target capability.

Basing presents some problems. Although the lasers could have an overall efficiency of about 10% at scale, producing the required multi-megajoule input electrical pulses would involve components too heavy for use in space or on aircraft. Ground based lasers would be relatively insensitive to those problems, since they could tap or generate the power required. While transmission through the atmosphere distorts the beam, active techniques for correcting beams have been developed. There is an additional requirement that the laser be provided a cloud free line of sight to the mirror, which was discussed above.

To exploit the whole of midcourse rather than just its latter phases, the ground based laser could be used to provide energy to mirrors carried above the bulk of the atmosphere on satellites, which would redirect the beam to the targets. The atmospheric correction is actually simpler for this case than for direct irradiation. The defender could launch the mirrors on a roughly vertical popup trajectory on detection and confirmation of attack. The mirror would require little preparation on reaching station, so essentially the whole midcourse would be available for discrimination.

For discrimination, irradiation of the whole of a 1 m object would be appropriate, since a MJ pulse would then give the 10-100 J/cm^2 that appears optimal. To achieve that spot size with a 0.4 micron laser from a range of 5,000 km would require a mirror of minor axis of $D = wR/d_S$ = 0.4 micron x 5000 km / 1 m = 2 m, and a major axis about 3 m for redirection. Such mirrors could be monolithic. The 30-50 s required to pop the mirror up would only represent a few percent reduction of the engagement time. Popup would extend the laser's range far beyond that available with basings, without incurring the full absenteeism and survivability costs of predeployment in space.

The ground based lasers themselves must also be made survivable, to which the principal obstacle is their size. With present scaling, the laser facilities would have dimensions of 5-10 m, which is compatible with modularization for dispersal, although large. For the rough \$ 100 /J costs from scaling prototypes, a 1 MJ discrimination laser would cost about \$100 M.[71] Prorated over the intercept of 100 RVs and 1,000 decoys, that would give a cost per discrimination of about \$ 0.1 M/object, which is well under the budget established above. The mirrors would also add cost, but designs for space optics of this intermediate size indicate that this increment should be smaller than that from the laser. The laser-mirror combination for discrimination is somewhat different than that for kill. For discrimination, an area of about 1 m^2 is irradiated with about 1 MJ/m^2, for a total of about 1 MJ; for kill an area of about 0.1 m^2 might be irradiated at about 50 MJ/m^2, or 5 MJ. For discrimination, mirrors about a factor of 3 smaller can be used, although it still requires lasers of significant size. A compromise could use lasers and mirrors of intermediate size to execute both missions sequentially.

If the attack involved 1,000 RVs that penetrated the boost phase with 100 credible decoys per RV, interrogating all 100,000 decoys during the roughly 2,000 s available in midcourse would require interrogation rates of about 50 objects per second, which would be within the capability of 5-10 repetitively pulsed lasers and mirrors. The power level for each, including the APS's factor-of-4 transmission loss would be about 4 x 1 MJ x 10 Hz = 40 MW. Since these performance levels are roughly an order of magnitude below those for lethality, midcourse discrimination could be the earliest application of ground based lasers.

Other lasers could also be used for discrimination, but their economics are less obvious. The nonnuclear lasers such as the various chemical and free electron lasers interact with targets in a quasi-continuous manner that does not generate impulse effectively. Thus, to discriminate they would have to irradiate the decoys and look for the production of some observable difference. But the energetics for doing so are only favorable in circumstances in which the basis for such observable changes is not obvious. If the decoys had the 10-30 kJ/g specific efficiency of a good ablator and the laser had a fuel efficiency of 500 kJ/kg, the (3 kg x 30 kJ/g) / 500 J/g = 200 kg of fuel required to totally erode each 3 kg decoy would not be attractive. If, however, the laser could gain a factor of 100 or more leverage by illuminating only a few percent of the decoy's surface, it could be roughly cost effective to sweep decoys with the laser, if boring a hole through the decoy produced some observable difference. That raises the possibility that the decoys could have some internal structure that would present confusing changes to the sensor. For that reason discrimination with other lasers is less certain and might be viewed as an adjunct low cost, low payoff adjunct role to a sounder mission.

2. Particle Beam Discrimination

Particle beams discriminate by irradiating objects with beams of hydrogen atoms, producing a spectrum of neutrons, gammas, and x-rays that can be detected remotely, and whose strengths are approximately proportional to the object's mass. That permits the discrimination of the heavy RVs from the light decoys, which give a much smaller return signal (Appendix B). Demonstrated beam parameters can support required interrogation rates and ranges, which do not appear to be degraded by nuclear backgrounds, the dominant countermeasure. The natural background is just detectable; that from nuclear bursts can be filtered enough that about half the RVs launched would have to be expended to significantly mask the threat.

The scaling of particle beams constellations for discrimination is closely related to that for boost phase defense, giving roughly the same 10-100 satellite constellations needed there for nominal parameters. Figure 4 shows the scaling of constellation sizes on the number of objects to be discriminated for retarget times of 1, 10, and 100 ms. For 1,000 penetrating RVS, the RVs plus 10% decoys would produce about 10,000 objects to be discriminated, which at a nominal retarget time of 1 ms would require no more than one platform to be in the engagement and thus about ten to be predeployed. That result would not change for 1% decoys, which would remain within the capability of a single platform. For that 10^5 object threat, the middle curve for a 10 ms retarget time would require about 30 platforms, which is less than that estimated for boost phase, for which the platforms could also be used. The top curve shows that a factor of 100 degradation of retarget time would raise the constellation size to about 300 platforms for 1% decoys, which would exceed the number required for the other layers. These estimates are based on a derivation analogous to the interior calculation for the boost phase, which indicates that the constellation sizes shown on the figure could overestimate the correct results by 50-100%, due to the neglect of the contributions of platforms outside the threat area.

While the beam's energy is set by the RV's mass, its current and dwell time can be varied. Thus, particle beams could not only discriminate decoys but also destroy the RVs detected--quite effectively with respect to both lasers and kinetic interceptors. Neutral particle beams of current design have masses large enough to require predeployment in space; those based on lighter and more efficient components could have masses of tens of tonnes, and hence be capable of being popped up on warning. Although the predeployment of either would represent a logistic burden, that need not be a major concern from the standpoint of survivability. The NPB's ability to discriminate decoys and kill the weapons concealed in them varies inversely with the square of the range, so the rate at which it can interrogate and kill targets improves when the object of the attack is the NPB itself.

Note that in extended engagements, rather than the simultaneous launches discussed above, the defense's performance would improve significantly, since the satellites' orbital motion would eventually rotate all of the discrimination platforms into the engagement area, largely eliminating the penalty for absenteeism. Absenteeism is also eliminated from the effective cost per inspection if the discrimination sensors are deployed from the ground rather than predeployed in space, which could be the case with advanced laser concepts with mirrors light enough to be popped up on warning, or particle beam platforms that were lightweighted to the apparent limits of current technology. Ground basing would produce a sensitivity to false alarms, but that penalty would have to amount to an order of magnitude to make ground basing more costly than predeployment in space for short interactions.

3. Summary

Discriminating the numerous credible decoys the offense could use is the principal problem in achieving effective midcourse intercepts. Passive techniques look useful in the near term, but interactive concepts are probably required for the long term. Several have been identified. Pulsed lasers and particle beams look particularly capable, giving costs per discrimination significantly below the value of the objects discriminated, and constellation sizes that are compatible with their secondary roles in the other engagement layers, even for threats of significant size and dilution.

B. Midcourse Interceptors

Lasers and standard nuclear weapons are not attractive for midcourse kill, because RVs are typically harder than boosters and buses by factors of 10-100 to thermal and impulsive loads. Kinetic energy concepts bypass that hardening; they have about the same lethality against RVs as boosters. Two generic kinetic energy concepts have been discussed: ground launched and space based KEW missiles. The former are being developed for an exoatmospheric reentry intercept system (ERIS), which uses homing interceptors with IR seekers with just enough field of view to reacquire already-discriminated targets, an attempt to exploit the approaches used successfully against similar targets in the tactical arena. Both ERIS and space based KEW interceptors are attempts to convert the technology demonstrated in the successful homing overlay experiments (HOEs) into practical systems by substituting smaller missiles and cheaper sensors. Limited range sensors with small fields of view should permit them to be small, and long flyout times should permit the use of efficient missiles.

1. Ground Based Interceptors

Interceptor performance is driven by the quality of discrimination that supports it. Ground based interceptors might cost about $ 3 M apiece, which is about a factor of 6-12 less than the RVs they attack. The costs for an ERIS are not known with precision since it is still in development, but <u>Missile Defense in the 1990s</u> surveyed available cost data and arrived at a figure of about $ 3 M per ERIS interceptor, divided about equally between hardware, launch, and operations, plus a fixed cost of about $ 10 B for satellite, aircraft, or probe sensors. Thus, in the intercepting bare RVs, ERIS would be very effective, but if the RV was accompanied by about ten undiscriminated decoys, the interceptor's effectiveness could drop to unity.

ERIS has certain intrinsic advantages relative to space based interceptors. The primary one is that ground basing avoids the absenteeism of space based systems, only a fraction of which would be in the battle space at the time of the engagement. That gives ERIS roughly a factor of 10 advantage over space based interceptors at present, an advantage that could become larger in the future, if boost phase launch areas and engagement times are further reduced. Whether that relative advantage also gives ERIS an absolute advantage over the threat's costs depends on the quality of the discrimination it receives.

If the decoy's mass was on the order of 10% of an RV's, by using half of its throw weight for decoys the attacker could provide about 10 decoys for each remaining RV. Then a blind interceptor would expend about $ 3 M for an expected gain of 2 x $ 20 M / 11 objects, or about $ 4 M/object, which would be roughly a draw. For 1% decoys, the exchange would be adverse to the defense by about an order of magnitude. Since such decoys are credible and the techniques for generating and dispensing them have been developed, it will be necessary to develop techniques for discriminating against them down to about the 10% level to make exoatmospheric ERIS intercepts effective. If either the laser or particle beam discriminants discussed earlier can be deployed efficiently, they should be able to provide discrimination to that level or better for roughly the costs indicated. Thus, a combination of ERIS and either popup or predeployed DEWs could provide an effective counter to even large and highly decoyed threats.

2. Predeployed Interceptors

Interceptors that are predeployed in space could also use small sensors and intercept velocities of a few km/s. They are distinguished from ERIS primarily by the broader coverage that results from their constant orbital motion. That makes it possible for them to engage the RVs throughout their trajectories and to cover targets distributed over the whole globe, but that also means that only about 10% of the interceptors would be able to participate in the engagement. Thus, engaging a stressing attack in which about 1,000 RVs penetrated the boost phase would require about 10,000 interceptors. Midcourse interceptors would be distributed roughly uniformly over the surface of the earth, but only those in the area swept out by the threat would be available to engage it.

For proper vertical dispersal of RVs and interceptors the engagement area is roughly $L(W + W')/2$, where $L = 10$ Mm is the length of the RVs' trajectories, $W' = 6$ Mm is the length of the Soviet launch area along the Siberian railway, and $W = 4$ Mm is the East-West extent of the U.S. For those values the engagement area is 50 $(\text{Mm})^2$, so a fraction of $f = 0.5L(W + W')/4pR_E^2 = 9.7\%$ of the satellites are available, where R_E is the earth's radius. A more accurate calculation that takes the contributions of the exterior interceptors into account replaces the expression above with $f = 0.5L(W + 4vt + W')/4pR_E^2$, where v is the interceptor's velocity and t is the effective time available for exterior interceptors have to fly in. For $v = 3$ km/s, $t = 300$ s, $4vt = 3{,}600$ km, and distributed launch gives $f = 13\%$. Point launch, $W' = 0$, gives 7.4%, which is significant, but much less of a reduction than that for boost phase concepts. Overall, about 10 times as many midcourse interceptors must be in orbit as the number of RVs intercepted.

The total cost of \$ 3 M/interceptor x 10,000 interceptor = \$ 30 B plus sensors would not be prohibitive, but it is awkward that the effective cost per interceptor is increased by that of the absentees to about 10 x \$ 3 M = \$ 30 M each, which approaches that of a decoyed RV, making cost-effective intercepts difficult. This cost estimate is based on the \$ 3 M per interceptor discussed earlier for ERIS, under the plausible assumption that their kill packages and divert velocities were similar. Discrimination must be nearly perfect for predeployed midcourse interceptors to be effective. For advanced threats the interceptor costs can be larger. Clearly it would be very useful to reduce the cost per interceptor by a factor of 3 to 10 to generate some margin, but that seems unlikely within the current interceptor concepts.

As discussed earlier for discriminators, in extended engagements rather than the simultaneous launches used for scaling calculations above, the defense's performance would improve significantly, since the satellites' orbital motion would rotate all of the interceptors into the engagement area in about the space of a day, which would eliminate the penalty for absenteeism. That could be much more important for interceptors than for discriminators because the expendable mass per intercept is so much more costly.

3. DEW Interceptors

As noted earlier, particle beams, because of their intrinsic ability to penetrate through RVs and shielding, can be used to kill RVs in midcourse, as well as to find them in highly dilute mixtures of decoys. The calculations and scaling estimates of Section II give the rough economics for NPB intercept. The curves in Fig. 4 are drawn for the discrimination of decoys, but when the retarget time S is small, the number of objects M and their hardness J enter only through their product MJ, so 1,000 RVs are roughly equivalent to 10^5 with masses about 1% of the RV's, for which the total constellation size would be about 10 platforms. If NPB platform costs scaled with their masses, that constellation could cost about 10 platforms x \$ 0.5 B/platform = \$ 5 B. If so, the particle beam 's cost per kill would be about $ 5 B / 1,000 RV = $ 5 M/RV, for which the defense would have about a factor of 10 margin in cost effectiveness. Particle beams might be one of the most clearly cost effective, predeployed midcourse interceptors in the near to mid term.

4. Summary

Absent saturation, degradation, or countermeasures greatly in excess of those discussed above present midcourse concepts that could provide an effective defensive layer. The principal issues are cost and coverage, which are largely driven by uncertainties in decoys and other countermeasures. Both ground and space based basings appear feasible for both discrimination and intercept. Ground based concepts require larger boosters to achieve the ranges needed to realize their full potential as preferential defenders, but their ground based facilities and sensors should be survivable even in stressing attacks. Space basing opens up more of the threat trajectory at the price of an order of magnitude increase of absenteeism, which degrades its economics and raises survivability issues.

Space basing of discrimination platforms has sufficient margin over the threat that its choice can be based on relative technical maturity and the need for the global coverage it provides. For interceptors, the additional phase space made available by midcourse operations may be required in later time intervals, but initially they would not appear to offset the additional cost penalties for basing the interceptors in space, as long as the boost phase and ERIS concepts retain their effectiveness. Major consideration in that shift are the rate of introduction of sensor countermeasures and decoys and of development of fast, mobile missiles and buses, which could degrade boost phase concepts seriously.

IV. COMPARATIVE ANALYSES

In the 3 years since the completion of the Defensive Technology Study, a number of reports have been released on the subject of strategic defense. Their main common themes have been the assessment of the readiness of technologies, the projection of their performance, and the estimation of the ultimate performance of of postulated defensive deployments. The sections above have discussed the key technical features; this section attempts to put both them and their projections into context.

A. The Defensive Technology Study (DTS)

The DTS was essentially the first open formal study of strategic defense with DEWs; it attempted to formulate an overall research plan for the development of a defense that could protect most if not all value targets. This stressing objective plus the lack of test data on key concepts and the lack of time to obtain it during the short time of the study reduced the DTS's output to an assessment that the objective was probably attainable, a rough technology road map for pursuing it, and a set of volumes summarizing the status of the various technologies. Those volumes, still largely current, contain much of the data and analyses reconstructed in the subsequent reports, but their classification prevented wide dissemination except through summaries. The DTS's recommendations favored DEWs. In part that was because of the lack of data on KEW performance; in part that was due to the individuals involved. But budgetary restrictions and data from field tests of KEW concepts began to shift the DTS goals immediately.

B. The Office of Technology Assessment (OTA)

The DTS was followed within less than a year by an initial OTA report that attempted to cover the same territory, an objective that was aided by its access to the DTS and other sources.[72] The draft product attracted significant attention. In part that was due to a number of errors that crept into the translation of how the concepts worked and where their development stood, but primarily it was due to the strong, and largely negative, conclusions that were based on analyses that were soon shown to be largely incorrect. The report usefully attempted to tie its conclusions to concrete, understandable scaling arguments, but the ones it presented did not, once corrected.[73] That generated popular discussion that was useful in the long term, since it did draw attention to inconsistencies in estimates and interpretations on important subjects, which aided in the resolution of several of them over the next few years.

It is likely, however, that the OTA report's lasting contribution will be its presentation of the counterpoint to the then optimistic popular mood in strategic defense when it said that a "near perfect system" could never be developed, that such expectations should not be the basis for discussion, and that mutual assured destruction (MAD) would "persist for the foreseeable future." Those statements, together with the assertion that any "less-than-perfect-defenses" would "allow the Soviet Union to destroy U.S. society," were among the catalysts that ultimately produced thought and insight into the value of less-than-perfect-defenses, approval for their investigation, and support for the deployment, as development permitted of less-than-perfect defenses as part of a phased progression. By the time the OTA issued its full report a year later, which used instead analyses and results largely in accord with those above, the earlier requirement that defenses had to be perfect just to be useful was replaced by a recognition that "defenses might be plausible for limited purposes...for which the technology is well in hand."[74]

C. The Union of Concerned Scientists (UCS)

The UCS reports also provided useful illumination of several key areas, although their attempts at scaling were somewhat misleading. The UCS's initial attempts to size and cost satellite constellations were about a factor of 10 higher than their current estimates, which are in turn almost a factor of 10 higher than the estimates above, as confirmed by one of the authors of the UCS reports.[75] The point is not an academic one. Despite the UCS's clarifications, only the first estimate seems to have imprinted itself on the popular debate, and the subsequent exchanges over improved solutions for the quantitative issues raised appear to have been followed in detail by only a handful other than those directly involved, although there was a much larger group of rapporteurs. In the long run, it is likely that the UCS report's contributions to quantitative issues will fade and their main contribution will rest on the expertise of its senior authors in the area of the fundamental countermeasures discussed above.

D. Soviet Committee Reports

A related series of reports was released by the Soviet Committee, which was chaired by the technical advisor to Soviet efforts on strategic defense. As noted above, those reports were somewhat chaotic, apparently reflecting access to the technical and quantitative issues primarily through the numerous conflicting U.S. sources cited. The quantitative analysis in the Soviet Reports is derivative of that in the early UCS reports, but it is so flawed algebraically as to invalidate any of its quantitative estimates. The reports are, however, useful in that they provide lengthy and apparently authoritative discussions of the aspects of strategic defense, such as crisis stability, most bothersome to the Soviets, to which there has been little U.S. response.

E. American Physical Society (APS) Reports

The recent APS Report has been discussed above and largely used as the technical basis for the discussion of the expected performance of most of the DEW concepts. Unlike the other reports discussed above, it largely confines itself to discussions of the principal concepts, their physical interactions, and their main technical issues. In the process, it makes much of the DTS's data and insights available to a much larger audience, including a number of issues such as x-ray laser penetration of the atmosphere, which were misleading as presented in the OTA and UCS reports, but not open for correction until now. There appear to be fewer points on which the APS Report is incorrect on technical detail, although there is some evidence of the deleterious effects of a half-year delay in publication. For instance, in the discussion of FELs and particle beams, all the technical issues listed as make-or-break had already been performed and reported in the months before the Report's release. Thus, for them it is already time for a revision to redetermine the next layer of technical obstacles.

On the Report's overall status summaries and projections the results are less positive. The APS Report provides an appendix that reproduces the limiting solutions discussed above--though not the combined solution, which was available throughout most of its deliberations--but those estimates were not used to systematically tie the various sections together. Instead, each section produced its own back-of-the-envelope calculations, which were uneven, to determine the requirements for each concept, which meant that both the mission requirements and technology development status were essentially floating. In some cases the current status statements were dated to the point of order-of-magnitude underestimates (e.g., average beam currents attained or power levels for chemical lasers). And requirements were overestimated by factors of 10 (e.g., excimer laser and particle beam energies for lethality) to 100 (FEL and excimer laser power requirements). Thus, their ratios, which were used as measures of the various concepts' readiness, were in error by factors of 10-100.

When these factors are corrected, as above, the APS's expressed concerns are largely obviated. The statement that chemical lasers "require power levels to be increased further by at least two orders of magnitude," is reduced to an assessment that they need to be scaled by about one order of magnitude, have demonstrated all key components separately, require mirrors that are within engineering capabilities, and have no major gas flow, power, or pointing issues remaining to be resolved. There is no basis in the technical body of the Report for the statement that chemical lasers, "because of their long wavelengths and other technical features...are perceived to be less attractive candidates for BMD" while "free electron lasers and excimer lasers are currently perceived as more attractive for BMD missions."[76] All would appear to compete about equally at present.

For the FEL, the Report's main concerns--operation in the visible and scaling injectors--have already been resolved through technical demonstrations. When scaled to the proper power level, 16 MWe rather than the APS Report's 1,000 MWe, their facilities should be modest. And excimer lasers, once pulse energies and kill rates are corrected down by a factor of 10 and powers down by a factor of 100, could be legitimately scaled in a single step to the levels required, from present tested modules. While particle beams "must be scaled up by two orders of magnitude in voltage and duty cycle with no increase in normalized beam emittance," the Report also observed that "the use of drift-tube linac as the major acceleration section appears relatively straightforward".[77] Other key technologies such as sources have already been demonstrated. The correct lethal fluences are about a factor of 100 lower than those required for lasers, so the correct beam power of 10-20 MW is well within current mass, power generation, and cooling capabilities. For the APS Report's deployment estimates, particle beams could be useful in the long term as well as the near term. The statements that all directed energy weapons and "space power, beam control and delivery, sensing tracking, and discrimination" need "two or more orders of magnitude improvement" are not justified on the basis of the technical material presented in the Report; its estimates of both peak and housekeeping powers are excessive by factors of 10-100.

Countermeasures are a continuing concern, but the APS Report's calculation of retrofit hardening against lasers underestimated its effective penalty on booster payloads by about a factor of 2, which could have a larger impact on the number of RVs launched. Other techniques such as spinning and depressed trajectories have less--or even favorable--impacts on the defenses. If boosters had to take these factor of 2 penalties for shielding, individual buses, and forced use of midcourse and replica decoys, the attack would be reduced by a factor of 10, even before launch. Countermeasures to particle beams are even more difficult, since the cost for shielding is exorbitant. The only useful measure appears to be deployment deep within the atmosphere, which is difficult, as the Report recognizes elsewhere.

In the midcourse, the main barrier to effective engagement is the ability to discriminate the many decoys that are possible there. Passive techniques could provide useful bulk filters, but for decoys that looked much like RVs--and vice versa--to passive and low power discrimination techniques, interactive measures would be required. Current candidates include pulsed lasers and particle beams, each of which can use known mechanisms to infer the masses of remote objects. Either could apparently discriminate large, dilute threats for costs small compared to those for the RVs, starting from either a popup or predeployed mode. Particle beams might be able to provide midcourse intercepts at significantly lower costs than KEW interceptors, and the survivability of DEW platforms should be enhanced because of their ability to discriminate decoyed attacks.

The APS Report begins with a disclaimer that "the technology of kinetic energy weapons (KEW) is not explicitly reviewed," and the report makes no significant comments on KEWs for early deployment. It is instead an attempt to sort out the main scientific and technical issues that could determine which directed energy concepts might be available in the mid to long terms if they were needed then either to initiate a delayed strategic defense deployment or to shore up emerging weaknesses of an earlier KEW deployment.

Over the course of time since the DTS, the relative priorities of DEW and KEW concepts have shifted to reflect the latter's maturity, so it should not be surprising that the APS Report "finds significant gaps in the scientific and engineering understanding of many issues [in DEW]." That status is perfectly appropriate for a group of technologies that are neither expected nor required to contribute for the next 10-15 years, an interval that would in fact provide the "decade or more of intensive research [which] would be required to provide the technical knowledge needed for an informed decision about the potential effectiveness and survivability of directed energy weapon systems."[78]. DEW concepts would appear to be about where they need to be to contribute in the longer term.

A related point in the Report's overview states that "typically technology is frozen several years before deployment."[79] Given the timelines involved, there is no need to be freezing DEW technology, but it should be noted that this argument applies to both the defense and offense, so it is not necessarily true that "The offense can use the long development test, and deployment time to respond." Given comparable development cycle times, comparable levels of technology could be deployed. It should also be noted that the challenges involved in developing missiles of the required hardness with useful payloads, fast burn boosters, whole new bus concepts, and mobile or survivable clustered launchers are not necessarily less stressing than developing the defenses required to meet them.

Statements in the Report about the relative difficulty of the development of DEWs and their offensive countermeasures should be evaluated in light of the fact that the group claimed no expertise and apparently received no information on that subject. The Report notes that "A DEW system designed for today's threat is likely to be inadequate for the threat it will face when deployed," but the concepts discussed throughout reflect the fact the DEWs are being developed for a very advanced threat. Today's threat could, as noted above, be met by a few tens of 5-4 chemical lasers, rather than the 25-fold brighter and much larger and faster acting lasers and particle beams now under investigation.

F. APS Council Statement

In addition to the Report by the APS Study Committee, the APS Council released a Statement that "is separate and broader than the subject matter and the conclusions of the DEW Study report," which states that "It is likely to be decades, if ever, before an effective, reliable, and survivable defensive system could be deployed [and that] the development of prototypes of SDI components in a state of technological uncertainty risks enormous waste of financial and human resources [so that] the SDI program should not be a controlling factor in U.S. security planning and the process of arms control [and] there should be no early commitment to the deployment of SDI components."[80]

It is clear from the above that it may well be a decade before any decision could or should be made on DEW effectiveness, let alone reliability. It also seems clear that demonstrating the simultaneous scaling by the final order of magnitude of the key features of the main concepts is probably more important than prototyping. Unfortunately, the distinction between simultaneous scaling demonstrations and protyping is not precise, and the definition of the "main concepts" tends to vary with individuals polled as well as over time. But the Council's statement that DEWs should not be a "controlling factor in U.S. security planning," does not mean that SDI itself should not, since the DEW is only a modest and decreasing component of it at present.

Whether or not developments would be wasteful would depend on the value of their technical objectives and the care devoted to their execution. To that point, it is useful to note that the APS Report did not criticize any of the experiments it discussed as being incorrect or even wasteful, only for providing partial answers to scaling questions. That is not unexpected, given that many of them were executed with modest funds by scientists who were motivated primarily by the science revealed by them. Finally, the elements of SDI that might be the subject of early deployment or discussion are outside the scope of the APS Report, and largely outside that of the APS itself.

G. Weakness in Comparative Process

In addition to the specific points of disagreement discussed, the comparison above indicates a weakness in the overall process that has been used to identify and evaluate the appropriate goals for strategic defense. Each of the reports discussed has been viewed as an answer unto itself. There has been relatively little effort devoted to identifying their common features, let alone the reasons for the disagreements between them. Such attempts have in fact generally been dismissed as "beating a dead horse." That has been the nature and fates of the OTA, UCS, and Soviet committee reports; there is no reason to believe that the order-of-magnitude misstatements in the APS Report will be treated any differently. On their release, which were largely media rather that technical events with lifetimes of one to two weeks, their conclusions have largely been trivialized and their analyses embalmed. The result is that one can at presently cite apparently legitimate reports and publications on opposed sides of almost any major strategic defense issue, with few attempts to reconcile them.

It is useful as well as humbling to look back at this growing list of reports, and to reflect that essentially every significant calculation and estimate has been done wrong in at least one of them. That is a reminder that the area of strategic defense, while describable even at the conversational level, does have a significant number of subtleties, which make the cross comparison of results even more important. At present, there is no adequate vehicle for doing so. The usual ones involve inappropriate delays and are not equally accessible to both sides of an issue. The publication of the APS Report, which was ostensibly intended to give physicists the basis for discussion of the DEW concepts, in the review with these misstatements intact and no opportunity for discussion, is likely instead to prematurely end discussion. It should be clear by now that both sides of the strategic defense debate have a common interest in providing a more open, thoughtful, and responsive vehicle for recording it, but there does not appear to be an obvious candidate for doing so.

V. SUMMARY AND CONCLUSIONS

The sections above have the used the technical aspects of the recent APS Report on DEW concepts, with some corrections for recent technical progress and for qualitative and numerical misstatements, as the basis for a discussion of the roles which these concepts might play in overcoming the weaknesses that could develop in earlier KEW deployments. From that discussion, it appears that DEW concepts could indeed play a useful, complementary role in reducing sensitivity to the spatial and temporal extent of boost phase engagements and in adding to the midcourse discrimination and intercept capabilities that may be needed in the mid to long term.

Viewed in that light, the DEW concepts are largely in appropriate stages of development to support their evaluation on the timescales needed. The chemical, free electron, and excimer lasers appear to be at comparable stages of development. The first two compete for space based applications on the basis of size, cost, and complexity; the second two compete for ground based roles on the basis of cost, beam transmission, and lethality. Particle beams are an interesting interstitial variant. They appear to be both efficient and lethal enough to compete with lasers in providing the attrition needed in the boost phase; they should have the right combination of penetration and conversion to compete in either predeployed or popup modes with pulsed lasers for the midcourse interactive discrimination role; and they seem to have the lethality required to intercept as well as discriminate midcourse RVs. The support, power, and technical assistance needed for each of the DEW concepts appear to be within the scaling limitations of current demonstrations.

In short, the DEW concepts are at roughly the right point in development to support their apparent natural role as a back-up for the more developed KEW concepts. All of the concepts could continue to be developed in parallel as is being done at present, but given the overlapping capabilities indicated above, some of them could be selected now for development in a simplified program with increased but apparently acceptable levels of overall technical risk. The APS reviewed the DEW concepts and concluded that there was not enough information to evaluate their ultimate potential and readiness for prototyping now, which is not a pressing problem given the actual times when such decisions are needed. Furthermore, the information collected by the APS Report is adequate to conclude that there are no known barriers to further progress and development, and that the projects needed to support decisions on further engineering development could apparently be executed within the timescales required for a complementary interaction with the main efforts in strategic defense.

APPENDIX A: Shielding Boosters Against Laser Radiation

For uniform stage hardening the APS's eq. 2.10 becomes

$$E^2 = [(X+P)/(X+P-M_{P1})][(Y+P)/(Y+P-M_{P2})], \tag{A1}$$

where the payload P includes bus hardening,

$$X = (1+f)(M_{P1}+M_{P2}) + M_{A1}+M_{A2}, \quad Y = (1+f)M_{P2} + M_{A2}, \tag{A2}$$

f is the ratio of structural material to propellant, $E^2 = \exp(V/c)$, and M_{XN} is the propellant (ablator) mass for X = P (A) of the first [second] stage for N = 1 [2]. The total payload is

$$P = [-b + (b^2-4ac)^{1/2}]/2a, \tag{A3}$$

$$a = E^2-1, \quad b = (E^2-1)(X+Y)-E^2(M_{P1}+M_{P2}), \tag{A4}$$

$$c = (X-M_{P1})(Y-M_{P2})-XY. \tag{A5}$$

Figure 3 uses the V = 7 km/s, c = 3.06 km/s, f = 0.15, M_{P1} = 146.2, and M_{P2} = 30.4 tonnes of the APS Report, although the first, second, and bus hardening masses are taken here to be 62.5, 25, and 12.5% of the total hardening mass, i.e., hardening masses for each stage are in proportion to their areas.

APPENDIX B: NPB Discrimination

If a NPB transmits a current A of particles of charge q for time t in a beam of divergence d, that produces a particle fluence $It/q(\theta R)^2$ at range R. A target of area $T < (\theta R)^2$ that produces n neutrons per proton would then create a neutron fluence

$$J = [It/q(\theta R)^2][nT/4\pi r_D{}^2], \tag{B1}$$

on a detector at range r_D. If the detector has an effective area A, the signal is the fluence times A. Equating it to the number of counts, S required for detection gives

$$Rr_D = (ItnTA/4\pi qS)^{1/2}/\theta, \tag{B2}$$

which shows the direct tradeoff between platform and detector ranges that is weakly dependent on beam and detector characteristics. For the matched case where $\theta R = T^{1/2}$,

$$r_D = (ItnA/4pqS)^{1/2}, \tag{B3}$$

which for I = 0.1 Amp, t = 1 ms, A = 1 m^2, and S = 100 gives r_D = 700 km, a useful standoff. The signal is $ItnA/q4pr_D{}^2$, which can be increased to the desired level by changing I, t, or r_D. The conversion efficiency n is roughly proportional to the target's mass. The return from a traffic decoy is just large enough to indicate its irradiation; that from a replica is adequate to differentiate it from an RV.[81]

APPENDIX C: Constellation Size for NPB Discrimination

Discrimination requires that the particle beam dwell on the object for a time

$$t = [SqE4pr_D^2/nTA]R^2/B, \qquad (C1)$$

so the quantity in brackets plays the role of a fluence to discriminate, J_D. For the parameters above, a beam of $E = 250$ Mev, and a $r_D = 500$ km sensor standoff, J_D is about 10 kJ/m^2, which is about a factor of 1,000 less than the fluence required to kill. The beam can discriminate objects at range R in a time $J_D/(B/R^2)$. Adding to this the time S required to retarget gives a discrimination rate

$$dM/dt = [(r^2+z^2)J_D/B + S]^{-1}, \qquad (C2)$$

where r and z are, respectively, the trackwise and cross ranges from the beam platform to the objects. For a simultaneous launch in which M objects penetrate the boost phase, the objects will pass each platform as approximately a sheet of lateral extent $W = 4{,}000$ km, which is the average of the launch and target areas' widths, and height $H = 1{,}000$ km, the vertical lofting that can be used without excessively dispersing their launch or arrival times. This area, $A = WH$, gives an average density of M/A, which is about 10^{-2} km^2, or average object spacing of about 10 km. Thus, the platform can begin with the objects near $r = 0$ as the wave comes into range and proceed outward in r until the objects are out of range. Since there are M/A objects per unit area, when the beam reaches radius r it has discriminated about pr^2M/A objects, so dM/dt can be replaced with $(pM/A)dr^2/dt$ and d/dt by Vd/dz, where V is the closing velocity, to produce

$$dr^2/dz = (A/pMV)[(r^2+z^2)J_D/B + S]^{-1}. \qquad (C3)$$

This result can integrated over $-H < z < H$, where H is the maximum range to determine the area swept out by each platform, which is $A_D = pr^2(z = H)$. The total number of satellites available in A must then be $n = A/A_D$; the constellation size is

$N = n/f$, where f is the fraction of platforms available to the midcourse. The phase space estimate of that fraction is $f = WL/4pR_E^2$, which is about 8% for ranges of about L = 10,000 km. But that must overestimate the correct constellation size because it neglects the exterior contribution, so the figure uses f = 10%. A more exact solution that extends the combined solution for boost is possible. For S very large $dr^2/dz = A/pMVS$, $A_D = 2HA/MVS$, $n = MVS/2H$, and N scales directly with S, as seen in the top curve of Fig. 4.

The hardness required to kill is about a factor of 100 larger than that required to discriminate, increasing the dwell time proportionally relative to the the retarget time. For $S = 0$, $dr^2/dz = (AB/pMVJ)/(r^2+z^2)$, so when S is small, M and J enter only through their product MJ. Thus, negating the 1% of the objects that are RVs takes about the same amount of time as the decoys, so the same constellation is well suited to discrimination, negation, or both. For J large r remains small compared to z, $dr^2/dz = (AB/pMVJ)/z^2$, and $n = MVJH/2B$, as seen in the bottom curve of the figure for $M > 10^5$.

Since r remains small compared to z by geometry in direct attack, for S small a single platform can discriminate about $M = 2B/VJH = 2 \times 2\times10^{19}$ W/Sr / (7 km/s x 10 kJ/m^2 x 1,000 km) = 600,000 objects.[82]

REFERENCES

1. G. Canavan, "Strategic Defense Concepts for Europe," A. Wohlstetter, F. Hoffman, and D. Yost, Eds., Swords and Shields (Lexington Books, Boston, 1987).

2. J. Fletcher, "The Technologies for Ballistic Missile Defense," Issues in Science and Technology, 1(1), pp. 15-29, Fall 1984.

3. The Strategic Defense Initiative: Defensive Technologies Study (U.S. Department of Defense, Government Printing Office, April 1984).

4. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society of the Study Group on the Science and Technology of Directed Energy Weapons," APS, New York, April 1987; Reviews of Modern Physics, 59(3), part II, July 1987.

5. J. Abrahamson, "Space-Based Defense: The View from the Top," Geopolitique, 9, pp. 6-28, 1985.

6. G. Yonas, "Strategic Defense Initiative: Politics and Science of Weapons in Space," Physics Today, pp. 24-8, June 1985.

7. G. Canavan, "Survivability of Strategic Defensive Concepts," Los Alamos National Laboratory Report LA-UR-86-1583, April 1985.

8. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 38 and Fig. 2.

9. H. Brown, "Is SDI Technically Feasible?" Foreign Affairs, pp. 435-454, March 1986; H. Brown, Johns Hopkins Foreign Policy Institute letter to author, 14 April 1986.

10. G. Canavan, "Scaling of NNK [Nonnuclear Kill] Boost-Phase Defensive Constellations," Los Alamos National Laboratory Report LA-UR-87-321, January 1987.

11. J. Gardner, E. Gerry, R. Jastrow, W. Nierenberg, and F. Seitz, Missile Defense in the 1990s (Marshall Institute, Washington, DC, 1987).

12. The U.S. Congress, Office of Technology Assessment, "MX Missile Basing," OTA-ISC-140 (U.S. Government Printing Office, September 1981).

13. Contractor Studies for the Defensive Technology Study, July 1983.

14. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 55.

15. H. Bethe, R. Garwin, K. Gottfried, and H. Kendall, "Space-Based Ballistic Missile Defense," Scientific American, 251(4), pp. 39-49, October 1984.

16. G. Canavan, H. Flicker, O. Judd, and K. Taggart, "Comments on the OTA Paper on Directed Energy Missile Defense in Space," Los Alamos National Laboratory Report LA-UR-85-3572, 6 May 1984, pp. 6-8 and Appendix A.

17. G. Canavan, et al., "Comments on the OTA Paper;" G. Canavan, et al., "Comparison of Analyses of Strategic Defense," Los Alamos National Laboratory Report LA-UR-85-754, February 1985.

18. G. Canavan and A. Petschek, "Satellite Allocation for Boost Phase Missile Intercept," Los Alamos National Laboratory Report LA-10926-MS, April 1987, submitted to Nature.

19. K. Gottfried and H. Kendall, "Space-Based Missile Defense," Union of Concerned Scientists Report, March 1984.

20. K. Gottfried and H. Kendall, op. cit., "Space-Based Missile Defense" and "Errata," undated.

21. R. Garwin, K. Gottfried, and H. Kendall, The Fallacy of Star Wars (Vintage Books, October 1984), p. 100; H. Bethe, et al., op. cit., "Space-Based BMD."

22. R. Garwin, "How Many Orbiting Lasers for Boost-Phase Intercept," Nature, 315, pp. 286-90, 23 May 1985.

23. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., Appendix B.

24. A. Carter, "Directed Energy Missile Defense in Space," U.S. Congress, Office of Technology Assessment, Background Paper OTA-BP-ISC-26, April 1984, Table 3.1, p. 20.

25. U.S. Congress, Office of Technology Assessment, "Ballistic Missile Defense Technologies," OTA-ISC-254 (U.S. Government Printing Office, September 1985).
26. R. Sagdeyev, Chairman of the Committee of Soviet Scientists in Defense of Peace Against the Threat of Nuclear War, "Perspectives on the Development of a U.S. Space-Based Anti-Missile System and Its Probable Effect Upon the Politico-Military Situation in the World," Moscow, 1983.
27. R. Sagdeyev, Chairman of the Committee of Soviet Scientists in Defense of Peace Against the Threat of Nuclear War, "The Large-Scale Anti-Missile System and International Security," Moscow, February 1986.
28. G. Canavan and H. Flicker, "Comments on the Soviet SDI Study," Los Alamos National Laboratory Report LA-UR-85-3728, December 1984.
29. T. Crites, "SDI Constellation Sizing Workshop," Aerospace Corporation Report TOR-0084A(5073-03)-2, July 1985.
30. J. Hammond, Director of Directed Energy, SDIO.
31. G. Canavan and A. Petschek, "Satellite Allocation," op. cit., Fig. 2.
32. G. Canavan and A. Petschek, "Satellite Allocation," op. cit., Fig. 3..
33. Canavan, et al., "Comparison of Analyses," op. cit., pp. 13-4.
34. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 178.
35. "SDI: Defensive Technology Study," Aviation Week and Space Technology, October 1984.
36. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 4.
37. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 60.
38. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 61.

39. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., APS Report, p. 2.

40. SDIO, "Comments on the American Physical Society Report on Directed Energy Technology," 23 April 1987.

41. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 5.

42. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 9.

43. R. Goldman and G. Canavan, "Interaction of Single-Pulse Optical Lasers with Targets in a Vacuum," Los Alamos National Laboratory Report LA-UR-84-2555, presented at the 1984 Laser Symposium at Oxford, England; published in Gas Flow and Chemical Lasers (Adam Hilger, Bristol, 1984), p. 125.

44. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 9.

45. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 9.

46. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 5.

47. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 270.

48. G. Canavan, R. Hunter, Jr., and A. Hunter, II, "Development and Application of Advanced High Energy Lasers," Los Alamos National Laboratory Report LA-UR-83-202, January 1983, in H. Mark and L. Wood, Energy in Physics, War, and Peace: Festschrift Celebrating Edward Teller's 75th Birthday (Israel, International Sciences, Spring 1987).

49. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 5.

50. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., pp. 144 and 272.

51. A. Carter, "Directed Energy Missile Defense," op. cit.

52. G. Canavan, et al., "Comments on the OTA Report," op. cit.

53. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 144.
54. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 11.
55. H. Flicker and G. Canavan, "Penetration of Neutral Particle Beam into the Atmosphere," Los Alamos National Laboratory Memorandum SDR:84-257, August 1984.
56. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 50.
57. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., pp. 5 and 149.
58. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 147.
59. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., APS p. 154.
60. SDIO, "Comments on the APS Report," op. cit.
61. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 35.
62. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 36 and Fig. 2.7.
63. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 37.
64. <u>Physics Today</u>, July 1986, p. 91.
65. <u>Physics Today</u>, July 1986, pp. 13-5 and 90-6.
66. R. Jastrow, <u>How to Make Nuclear Weapons Obsolete</u> (Little, Brown, and Co., Boston, 1985).
67. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 29.
68. G. Canavan, "Survivability of Space Assets," Los Alamos National Laboratory Report LA-UR-86-4108, December 1986.
69. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 2.
70. G. Canavan, R. Hunter, and A. Hunter, "Development and Application," op. cit.

71. G. Canavan, R. Hunter, and A. Hunter, "Development," op. cit., p. 20.
72. A. Carter, "Directed Energy Missile Defense in Space," op.. cit.
73. G. Canavan, "Comments on the OTA Paper on Directed Energy," and G. Canavan and A. Petschek, "Satellite Allocation," op. cit.
74. U.S. Congress, Office of Technology Assessment, "Ballistic Missile Defense Technologies," pp. 32-4.
75. R. Garwin, "How Many Orbiting Lasers," op. cit.
76. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 2.
77. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 149.
78. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p.2.
79. N. Bloembergen and C. Patel, Chairmen, "Report to the American Physical Society," op. cit., p. 20.
80. APS, "Statement on the Strategic Defense Initiative," New York, American Institute of Physics, 24 April 1987.
81. G. Canavan, "Active Discrimination with Lasers and Particle Beams," Los Alamos National Laboratory Report LA-UR-85-2, April 1985.
82. G. Canavan, "Survivability of Strategic Defense Concepts," Los Alamos National Laboratory Report LA-UR-85-1583, May 1985; "Survivability of Neutral Particle Beam Platforms," Los Alamos National Laboratory Report LA-UR-85-2476, July 1985; and "Survivability of Space Assets," Los Alamos National Laboratory Report LA-UR-86-2476, December 1986.

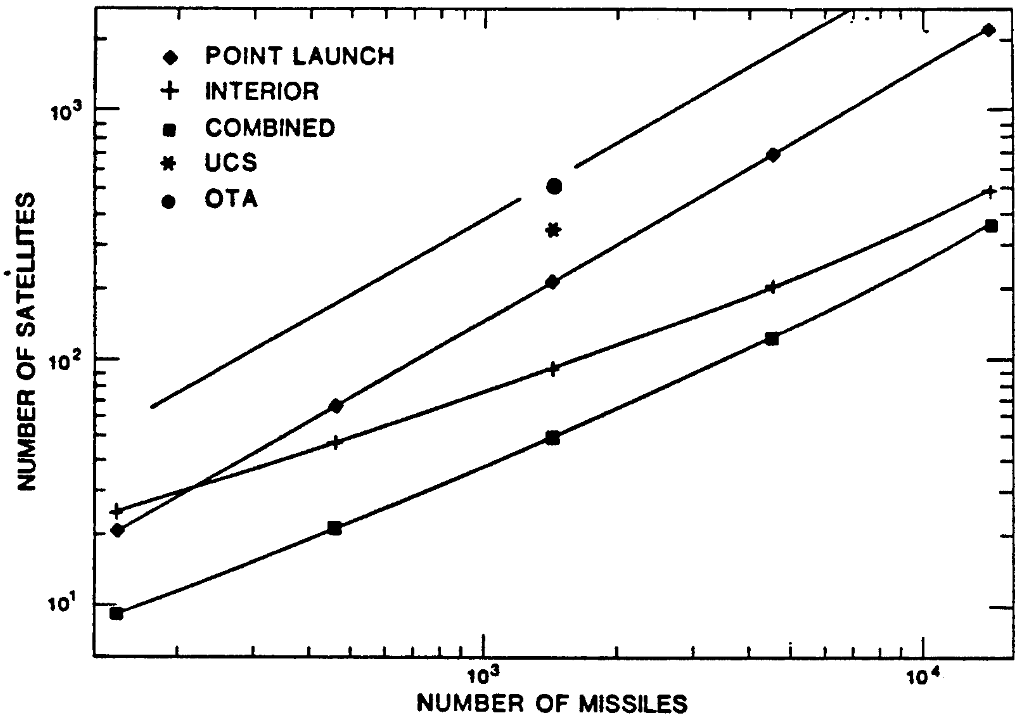

Fig. 1. Constellation size vs threat size.

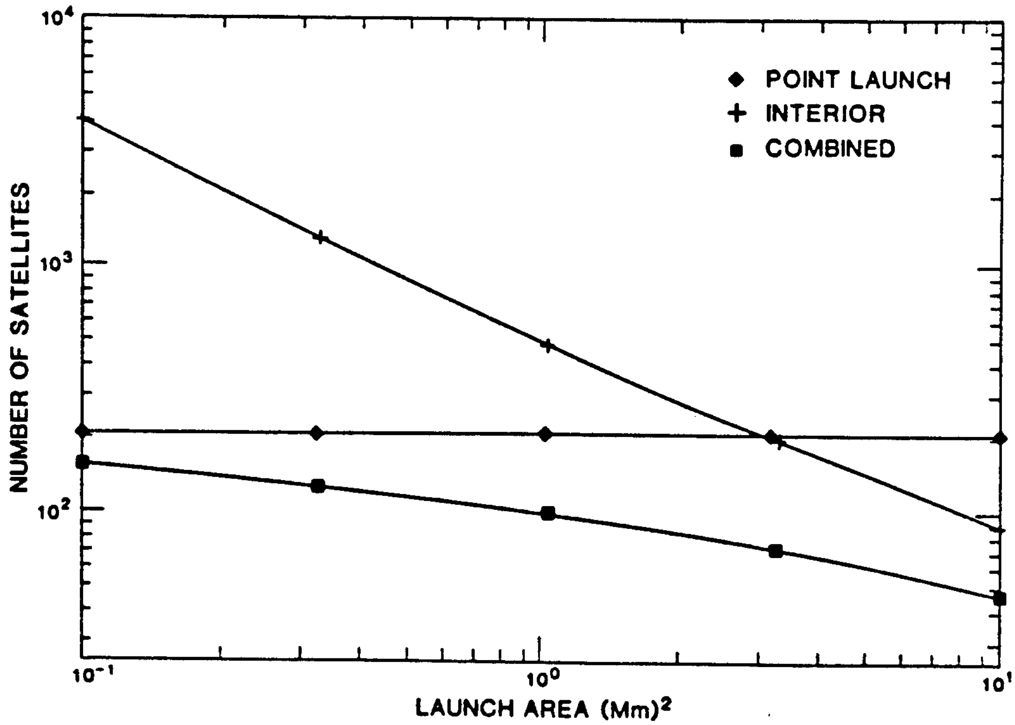

Fig. 2. Constellation size vs launch area.

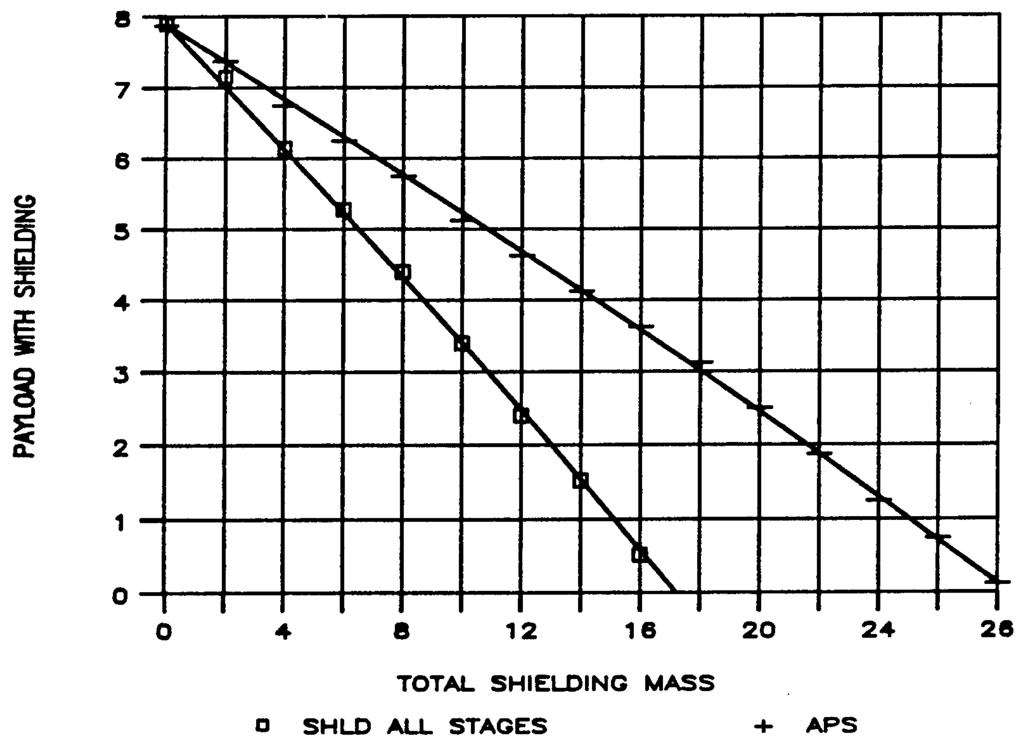

Fig. 3. Payload penalties: shielding all stages vs APS.

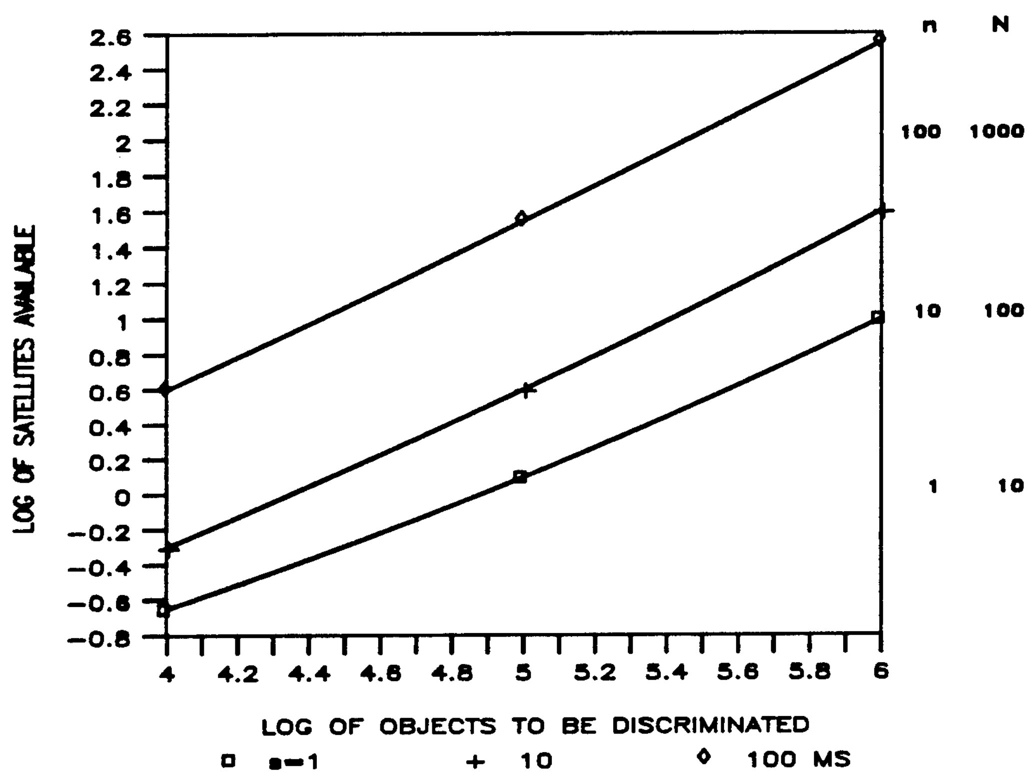

Fig. 4. Particle beam discrimination constellation size.