LASER WINTER: GROUND INCENDIARY CAPABILITY OF BALLISTIC MISSILE DEFENSE LASERS

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Space-based laser weapons sufficient to defend against a superpower ICBM attack would, with high probability, also be sufficient to burn out the centers of all of the combatant's major urban areas. Smoke from the resulting firestorms would, most likely, initiate a globally disastrous climatic perturbation.[#]

Preamble: *The alalysis in this paper was completed in 1991, but nothing has developed since to alter the conclusions. No major new technical considerations have emerged. No significant new political considerations have emerged. Since then the USSR has ceased to exist and its successor, Russia, has ceased to be a viable competitor to the USA. However, with the USA recently abandoning the United Nations and the arms treaties and obviously initiating a campaign to rule the world militarily, an alliance of economically developed nations combined with the militarily developed Russia is likely to emerge as a viable competitor. US relations with France and Germany have turned antagonistic. Russia recently announced the initiation of its own SDI program.*

INTRODUCTION

The proclaimed objective of the Strategic Defense Initiative (SDI), and its subsequent renamings, is to render nuclear weapons "impotent and obsolete." Space and ground based ballistic missile defense (BMD) systems on both sides would eliminate the threat of nuclear war and the resulting nuclear winter. This is the ultimate objective of the SDI, although lesser, intermediate objectives have been emphasized.

The least unpromising proposal[1] for the boost phase intercept layer of the SDI is the high power laser, either chemical lasers in orbit or free electron lasers on the ground reflecting from mirrors in orbit.

Ballistic missile defense faces extremely challenging problems with technical feasibility, computer programming, intra-atmospheric delivery systems (cruse missils, terrian skimming bombers, terrorist infiltration, etc.), cost effectiveness, and strategic stability.[1,2,3,4] This paper presumes that all of these challenges have somehow been met, so that nuclear weapons have indeed become obsolete. It assumes that each combatant has scrapped its thereby useless nuclear missiles in the face of the other side's impenetrable defenses.

In doing so, however, it will have freed its system for possible other uses. We further assume -- since necessity for BMD presumes the impossibility of ending any arms race by negotiations -- that the great powers will continue to seek military superiority, although through non-nuclear weapons. Even with the economic collapse of one side, the research, development, and deployment of first strike weapons and defenses continue. The trillion dollars of laser firepower in space might represent an awesome capability, and that capability might have uses other than against nuclear missiles.

This paper analyzes the capability for incendiary attack against cities. If this capability is strategically significant, then it may become the new arena in the struggle for military superiority. Even if some other weapon proves superior, BMD lasers will still be in existence. The expense for the additional controls and programming for ground incendiary capability will have

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[#] Key Words: Atmospheric Propagation, Atmospheric Perturbation, Nuclear Winter, Thermal Blooming, Incendiary Weapons, Mass Fire, Firestorm, High Energy Lasers, Laser Weapons, Strategic Weapons, Strategic Defense Initiative, Ballistic Missile Defense, Anti-Ballistic Missile Weapons

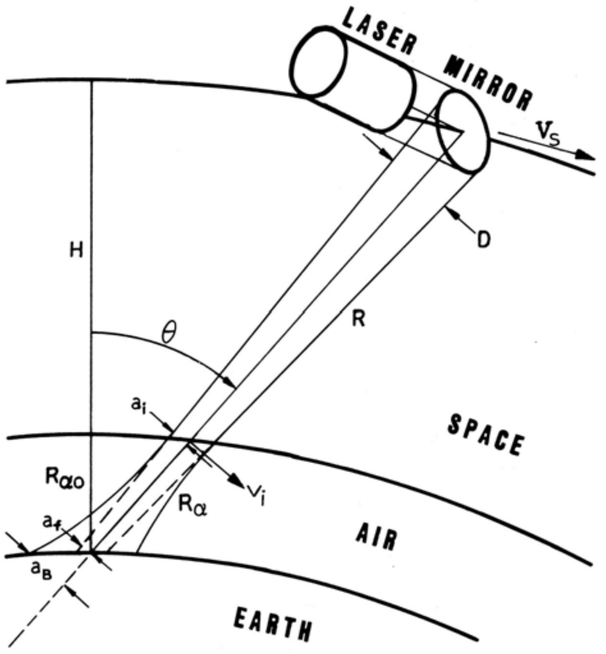

Figure 1. Geometry of an Orbiting Laser BMD Attacking a Ground Target.

A BMD laser in orbit with a velocity of V_s irradiates a fixed point on the ground. The laser beam slews (pivots) about that point on the ground. The velocity of points along the beam increases to v_i at the top of the atmosphere (whose density is approximated as a step-function). Thermal blooming spreads the radius of the illuminated spot from a_f to a_B.

been trivial. So we must assume that if significant incendiary capability is possible, it will have been included. In diplomatic struggles between great powers -- and between great powers and lessor powers -- all uses of all military capabilities enter the calculations of both sides in any given confrontation.[5] If diplomacy fails in various ways, any or all of these capabilities may be exercised.

An unavailable study[6] has been said to conclude that such a system of lasers might be capable of initiating 10^8 separate fires at the surface of the Earth. As few as 500 separate fires in a city may unite[7,8,9,10,11,12] to form a "large-area-fire." This fire phenomenon occurs when the plumes of many individual building fires unite to form one great plume. Hurricane force radially inward winds develop at ground level, and the smoke-laden plume can extend into the Stratosphere. As has been customary, we often term such a large-area-fire by the more common but less precise term "firestorm."

Nuclear winter studies[13,14,15,16,17,18] show that firestorms and other mass fires induced by 100MT of explosives on city centers would, most likely, inject enough smoke into the upper atmosphere to initiate a climatic perturbation that would be disastrous.[19,20]

Indeed, a back-of-an-envelope study[21] shows that the BMD lasers may well have the capability for such a "laser winter." This paper provides a rigorous formulation for that possibility, using sufficient or best available theory for the influential physical phenomena. Where existing theory or data are weak, sensitivity analyses establish the conclusion to a considerable level of statistical confidence.

The physical phenomenon that is the most influential is thermal blooming. Thermal blooming is the diverging of a laser beam caused by the beam heating its path through the atmosphere. The center of the beam is the most intense, heats the air the most, and reduces the refractive index of the air the most. This produces an index of refraction gradient principally in the form of a negative lens, which diverges the beam. Thermal blooming is a serious consideration in most high-energy laser applications in the atmosphere and might diverge the beam to the point where it is incapable of igniting fires. This seems especially likely for the BMD lasers with their long path, through the Earth's entire atmosphere (beam deflection also occurs but has little consequence[22]). Indeed a superficial blooming analysis shows little fire capability. Insight provided by the theory, however, shows that if the laser power is reduced to an optimum value that maximizes the ground irradiance, an immense capability emerges.

NOMINAL BOOST PHASE SYSTEM

To establish a nominal system with which to work,[23] assume a threat from 1400 Russian ICBMs that have become "responsive" to BMD by

1. clustering of the ICBMs (counter countered by optimizing laser orbits for concentration over the cluster),
2. reduced booster burn time from 100 to 50 sec,
3. ablative coatings to increase the hardness 10 fold to 1000MJ/m^2, and
4. rotation of the missile.

Adoption of a nominal system[2] that is widely used but inconsiderate of these responses and application of a well-established formulation[3] for countering these responses gives a required capability that is satisfied by

N_L = 360 phased arrays x 10 lasers each x 2 BMDs (US + Russia),
P = 20 megawatts maximum power output/laser,
λ = 3.8 μm wavelength (Deuterium Fluoride, DF, laser),
D = 10 meter diameter focusing optics,
H = 1000 Km orbits, and
0.1 sec retarget time.

This system is comparable to, and somewhat brighter than, a proposed system.[1]

GEOMETRY

Figure **1** illustrates the geometry of a laser boost-phase system. The atmosphere is modeled as a step function with sea level density to an altitude of $R_{\parallel 0}$=5Km and zero beyond. Such a layer of this thickness gives[24] about the same total absorption as a path through the actual atmosphere from the common continental elevations to space.

Assume that each laser of a phased array can be pointed independently over distances of meters by use of the active optics of the focusing mirror and over distances of kilometers by tilting a small mirror in the optical train of each laser[3]. Each laser attacks from a nominal zenith angle of θ=60°, at which the path to the target is R=2000Km. The resulting $R_{\parallel}$=10Km atmospheric path is a very small part of the total path, so that the beam throughout the atmosphere is essentially collimated. The initial beam radius a_i and final beam radius a_f (without thermal blooming) are both approximately equal to the diffraction limited focal spot.

$$a_f = a_i = 0.4\lambda R/D \tag{1}$$

In order to maintain a fixed illuminated point on the ground, the beam slews (sweeps in an angular fashion as shown in Figure **1**) through the air so that the velocity at points along the beam varies linearly from v_f=0 at a_f to

$$v_i = V_s R_{\parallel 0}/R, \tag{2}$$

(perpendicular to the beam) at a_i, where

$$V_s = (7.88\text{Km/sec})[r_e/(r_e+H)]^{1/2} \tag{3}$$

is the orbital velocity and r_e=6378Km is the radius of the Earth.

CW THERMAL BLOOMING

In actuality, the beam does not remain collimated but heats its path and diverges. The divergence, or thermal blooming, varies with the pulse structure of the laser output. Concentrating the power into short, widely spaced pulses can often reduce blooming,[25,26,27] but computations[24] for the above system show that air breakdown (ionization) or stimulated Raman scattering sets in and destroys the beam before significant blooming reduction occurs. Non-CW lasers therefore may have no ground incendiary capability. The chemical laser is naturally CW. The free electron laser is not, but designers can readily make it nearly CW.[1,24] That is, although it has a multipulse structure -- a rapid train of nano to picosecond pulses in microsecond clumps -- the pulses can be spaced sufficiently close and the clumps lengthened enough to approach CW and thus avoid air breakdown. Indeed this may be necessary to transmit the beam of this ground-based system up through the atmosphere to its orbiting mirrors. Raman cells[1] have been proposed so as to approach CW even more.

Therefore, only a CW blooming model needs to be developed. To the unbloomed spot area A_f on the ground, blooming adds the area A_B, which spreads the laser power over the sum.[25] The effects of pointing jitter and atmospheric scintillation may similarly be put in terms of areas that add to A_f, but these areas were found[24,!] to be negligible relative to A_f+A_B. The irradiance without blooming is

$$I_u = \frac{Pe^{-N_E}}{A_f} \tag{4}$$

where N_E is the attenuation number (scattering plus absorption). The irradiance with blooming is[25]

$$\frac{I}{I_u} = \frac{1}{1+A_B/A_f} \tag{5}$$

State-of-the-art thermal blooming computations generally require a numerical computer program. Gebhardt[25] presents approximate[28] results in closed form and maintains that they are sufficient for rough calculations. Transformation[24] of Gebhardt's formulation into the definitions used by a more primitive formulation[29] allowed direct application to the BMD geometry.

An indeterminacy is avoided. It occurs at the ground, where the beam is stationary and the air still. The following results avoid it by the common approximation[24,29] of setting the slewing to zero, $v_f=v_i$, and compensating by replacing the v_i in the convection distortion parameter (N_c, presented below) by the average velocity, $v_i/2$, over the path.

The resulting model is

$$\frac{A_B}{A_f} = 0.198C\left(\frac{N_c}{P}\frac{a_i}{a_f}g_G(N_E)q_G(\frac{a_i}{a_f})P\right)^q \tag{6}$$

where q & C are constants dependent on the laser beam cross section,[25] 1.565 & 0.510 for our infinite gaussian cross-section, and where the "convection distortion parameter," N_c, is given by

$$\frac{N_c}{P} = \frac{2(-n_T)N_{Eabs}R_\alpha}{n\rho c_p v_i a_i^3} \tag{7}$$

where

N_{Eabs} is the absorption # (all absorption and no scattering),
n=1.000273 is the index of refraction of the air,
n_T=-1.4x10^{-6}/°C is the index of refraction temperature gradient,
D=1.292gm/R is the density of the air, and
c_p=1.01J/gm°C is the specific heat of the air at constant pressure.

The "range correction factor" in Eq. (6) is given by

$$g_G(N_E) = e^{-N_E/2} \tag{8}$$

and the "focus correction factor" is given by

[!] The jitter must be less than the unbloomed spot size for the BMD capability to be present, therefore if the area alone caused by jitter is A_J, then the quantity **(** = $1+A_J/A_f$ will be no more than about 1.5. Rederivation of Eqs (12) and (13), the later derived optimum laser power and maximum ground irradiance, give a power change by a factor of **(**$^{1/q}$=1.30 and an irradiance change by a factor of **(**$^{(1-q)/q}$=0.86, which give trivial changes to the results of this paper.

$$q_G\left(\frac{a_i}{a_f}\right) = \frac{a_i/a_f}{a_i/a_f - 10/2\pi}\ln\left(\frac{2\pi}{10}\frac{a_i}{a_f}\right), \quad for\frac{v_f}{v_i} = 1 \tag{9}$$

OPTIMUM LASER BEAM POWER

This formulation gives the irradiance incident at the ground for any chosen power P of the laser beam. By letting P be the maximum power that the laser can achieve, one would expect to obtain the maximum irradiance at the ground. It is well known that this is not the case. Gebhardt[25] derives a "critical power" P_c that gives the maximum irradiance. This may be lower than the maximum laser power in which case the incendiary effect would be increased by decreasing the power. This is the primary insight that blooming theory provides to convert largely ineffectual laser beams into ones very effectual for initiating fires.

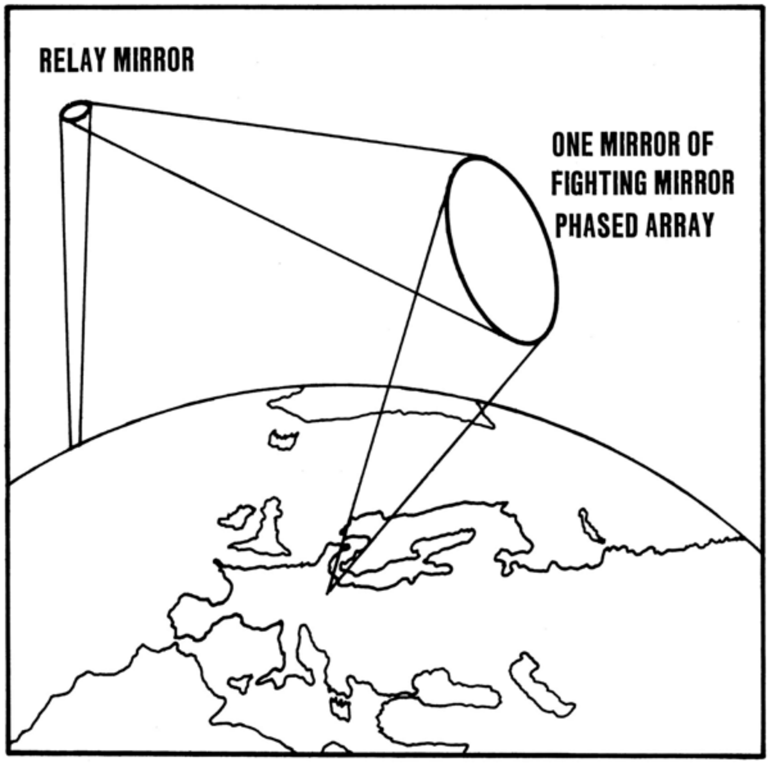

Figure 2. Geometry of a Ground Based Free Electron Laser BMD.

Eqs. (4)–(9) determine the irradiance I in terms of P. They give

$$I = \frac{e^{-N_E}}{A_f}\left(\frac{P}{1 + C_x P^q}\right) \tag{10}$$

where

$$C_x = \frac{A_B}{A_f}P^{-q} \tag{11}$$

is a constant implicitly independent of P. Solving dI/dP=0 for P gives the "critical power," at which I is maximum.

$$P_c = \left(\frac{1}{C_x(q-1)}\right)^{1/q} \tag{12}$$

Substitution into Eq. (10) gives the sought for maximum possible ground irradiance.

$$I_c = \frac{P_c}{A_f}e^{-N_E}\frac{q-1}{q} \tag{13}$$

Combining all results generated thus far, and letting $a_i/a_f=1$ (an effectively collimated beam incident into the blooming medium), we obtain the rather simple overall system performance equation,

$$I_c = C_y \frac{\sqrt{r_e/(r_e+H)}\lambda\cos^2\theta}{R_{\alpha 0}\alpha_a D}\exp\left(-\frac{R_{\alpha 0}(\alpha_a+\alpha_s)}{2\cos\theta}\right) \tag{14}$$

where "$_a$ and "$_s$ are the attenuation coefficients for absorption and scattering respectively, and where

$$C_y = \frac{0.4(7.88Km/s)}{0.786(2\pi)}\left(\frac{1}{0.198C}\right)^{1/q}\left(\frac{1}{q-1}\right)^{1/q}\frac{q-1}{q}\frac{n\rho c_p}{(-n_T)} = 1.34\times 10^{12}W/m^2 \tag{15}$$

is a constant independent of all parameters whose variation is of interest. (Of course if $P_c>P$, there is insufficient power to attain I_c, but P_c exceeded the 20MW maximum laser power nowhere over all reasonable ranges of parameter values for the BMD application.)

Equations (14) and (15) assume that diffraction limited focusing gives the greatest optimized irradiance. But only for **8**/*D*< . 2**:**m/10m does optimized irradiance increase with decreasing beam size down to the diffraction limit. Below that wavelength, diffraction limited focusing gives a rather ineffectual optimized irradiance. For the additional optimization available through optimum defocusing, in Eq. (14) set

8/*D*=2**:**m/10m, for **8**/*D*< . 2**:**m/10m. (16)

The above equations and their required inputs from the atmosphere and the laser/target geometry would allow the weapons control system to adjust the laser power and defocusing to produce a maximum ground irradiance for each shot.

FREE ELECTRON LASER BMD

Of equal interest[1] to the chemical laser is the free electron laser,[30] which is much too heavy to be placed in orbit. As illustrated by Figure **(12)**, a laser on the surface will transmit to a large "relay" mirror in high orbit and reflect to a smaller "fighting mirror" in low orbit.[1,4] Since the free electron system must meet the same requirements as the chemical system, the fighting mirror must consist of a phased array of 10 10-meter mirrors and have the same focusing and pointing capabilities as the mirrors of the orbiting chemical laser array. Blooming might disrupt the upward propagation as well as the downward, but the postulation of booster attack capability presumes that the 20MW somehow reaches each member of a fighting mirror array (by increased laser power, adaptive optics, etc.). The above derived formulation therefore applies identically to the free electron system.

ATMOSPHERIC ABSORPTION

Atmospheric absorption is a critical parameter since it governs the heating that blooms the beam.[31] In the most transmissive regions of the IR spectrum, molecular absorption can be reduced indefinitely by fine tuning a narrow lined laser between absorption lines.[32,33] However, aerosol absorption (although usually considered trivial relative to molecular absorption) is continuous[34,35] and does not have fine lines to tune between. It forms a continuum limit below which absorption cannot be avoided. On the clearest days it is about "$_a$=0.004/Km at 3.8**:**m (the most transmissive wavelength in the IR spectrum). (This sea level figure was obtained from a figure for the absorption vertically through the entire atmosphere, by equating the path integrated absorptions.)

This 0.004/Km is about the minimum absorption possible. But extremely powerful lasers may not be developable to exploit it. They may not attain fine single lines, and powerful chemical lasers appear possible only at a few discrete wavelengths. A higher absorption of "$_a$=0.016/Km is not exceeded[36] over 0.1**:**m of the IR spectrum. This is enough bandwidth for development of a free electron laser that is spectrally sloppy. The absorption "$_a$=0.065/Km is not exceeded[36] over 0.8**:**m, which probably is bandwidth enough for the occurrence of a developable chemical laser line. (But it must be noted that the promising DF $P_2(8)$ line is precisely at 3.8**:**m, where "$_a$=0.004/Km.) The absorption "$_a$=0.15/Km is not exceeded over 2.6**:**m, which should be enough bandwidth for any consideration.

FIRE IGNITION

The comparable irradiances required to initiate fires are available from nuclear weapons tests.[7,&] They give the fluence, F_i, required to ignite various typically exposed materials by flashes of differing durations, T. A rough mean line through this data is

$$F_i = (24W/cm^2)T + (80J/cm^2). \quad (17)$$

This expression compares also with data[37] on the ignition of structures by nuclear flashes (for 60-90% probability of ignition). Letting $F_i = I_c T$ and solving for T, we obtain the dwell time for ignition of the average flammable material.

$$T = (80J/cm^2)/[I_c - (24W/cm^2)] \quad (18)$$

This expression shows that as little as $24W/cm^2$ can start fires and that as little as $35W/cm^2$ can start fires in less than 7 seconds.

Table I. SURFACE INCENDIARY THREAT FROM BMD LASERS

Chemical laser BMDs would threaten nuclear winter effects where the smoke exceeds the 15Tg threshold, figures shaded. (Smoke mass for other than 65Tg was computed from a distribution of fuel density with attacked area, assuming the greatest fuel densities attacked first.) Free electron laser BMDs would threaten nuclear winter effects where the irradiance exceeds the $24W/cm^2$ necessary to initiate fires. This happens to correspond to figures shaded according to the above 15Tg criteria. (The SMOKE and BOMB EQUIVALENT figures are inapplicable to the free electron laser because unlimited fuel allows unlimited numbers of shots wherever the irradiance exceeds $24W/cm^2$.)

ABSORPTION COEFFICIENT		ZENITH ANGLE OF ATTACK				
		10°	45°	60°	75°	
"$_a$=0.004Km^{-1}	OPT POWER	5.6	5.6	5.6	5.7	MW
Not excd over	GROUND IRR	2400	1200	610	150	W/cm^2
0:m / 1616:m	ILLUM DIA	0.5	0.8	1.1	2.2	m
	TIME/SHOT	0.03	0.07	0.12	0.6	sec
DF 3.8:m line	BOMB EQUIV	510	260	120	26	MT
	SMOKE	140	100	72	34	Tg
"$_a$=0.016Km^{-1}	OPT POWER	1.4	1.5	1.5	1.6	MW
Not excd over	GROUND IRR	580	290	140	33	W/cm^2
0.1:m / 1616:m	ILLUM DIA	0.6	0.8	1.2	2.5	m
	TIME/SHOT	0.14	0.3	0.7	9	sec
Free e$^-$ laser	BOMB EQUIV	460	220	100	7	MT
	SMOKE	130	96	65	16	Tg
"$_a$=0.065Km^{-1}	OPT POWER	0.4	0.4	0.5	0.65	MW
Not excd over	GROUND IRR	120	61	28	4.1	W/cm^2
0.8:m / 1616:m	ILLUM DIA	0.6	0.9	1.5	4	m
	TIME/SHOT	0.8	2.2	23	0	sec
Chemical laser	BOMB EQUIV	300	100	9	0	MT
Free e$^-$ laser	SMOKE	110	65	18		Tg
"$_a$=0.150Km^{-1}	OPT POWER	0.2	0.2	0.3	0.7	MW
Not excd over	GROUND IRR	44	19	8	1	W/cm^2
2.6:m / 1616:m	ILLUM DIA	0.8	1.3	2.6	10	m
	TIME/SHOT	4	4	4	4	sec
Chemical laser	BOMB EQUIV	110	0	0	0	MT
Free e$^-$ laser	SMOKE	70	0	0	0	Tg

For an example of the irradiance available from the BMD, Eqs. (14) and (15), for nominal parameter values,

> 2=60° attack zenith angle, and
> "$_a$=0.016/Km (allows 0.1:m of the IR spectrum for choice of a laser),
> give I_c=140W/cm^2.

This result implies that a laser that can be developed to operate within 0.1:m around 3.8:m -- a free electron laser or a DF chemical laser -- would be capable of starting fires within practical times and over a wide region of the sky. For a second example,

> 2=10° attack zenith angle, and
> "$_a$=0.15/Km (allows 2.6:m for choice of a laser)
> give I_c=44W/cm^2.

This shows a generous spectrum within which to develop a dangerous chemical laser other than a DF laser.

NUMBER OF FIRES

For the number of such fires that the entire boost phase intercept systems could initiate, consider the orbiting, chemical laser. The nominal system requires an operating time of at least 50 sec, the assumed booster burn time. To include a margin for insurance, let each laser have enough fuel for three times this minimum, for 150 sec at the power P=20MW required for booster kill. But the optimum powers that occurred in the above two evaluations were only P_c = 1.5 and 0.2 MW respectively.

[&] The heating effectiveness of a laser radiation, which is single wavelength, can be compared to that of the nuclear explosion flash, even though it is broad spectrum. Although each specific material may have a strong dependence on the specific laser wavelength, the ensemble average over the wide variety of materials exposed should approximate that of a broad spectrum. Even the predominantly visible spectrum of the nuclear flash should not give significantly different heating relative to an infrared line from a laser, because there appears no strong trend toward greater or lessor reflectivity of materials as the wavelength is varied into the IR.

Assuming that the laser can be turned down to those powers and that the fuel would be consumed at proportionally slower rates, then the operating times become 2000 and 15,000 sec/laser respectively.

Equation (18) gives the exposure times required for a fire to be 0.7 and 4 sec for the above two cases, so that the number of shots/laser potentially capable of starting fires are 3000 and 3500. These multiplied by the N_L=7200 lasers of the systems give the capability of $22x10^6$ and $25x10^6$ possible fire ignitions respectively.

Of course, the actual number of buildings set on fire will be much lower than these figures. Burnables outside of or on the outer surfaces of buildings rarely sustain fire[7,9,37] (without the radiant heat from surrounding fires). Essentially, laser radiation must get through windows. The obvious countermeasure is to prevent light from getting through any window. Unfortunately, the purpose of windows is opposed to this countermeasure, and public discipline will therefore not be perfect. Reconnaissance satellites might be continuously assessing opportunities. A nominal success rate of 1/90 building fires per laser shot gives $0.25x10^6$ building fires for the above examples.

FIRESTORMS

Experiences with firebombing in World War II,[7,9] experiments,[12] and theory[10,11] establish the large-area-fire as a predictable phenomenon.

The criteria for the smallest possible firestorms, however, are somewhat controversial.[27] Some authorities[7] considered the minimum to require half of the structures on fire in an area of 1.3Km^2 that contains 4gm/cm^2 of combustible materials. For a typical average city, Nashville, Tennessee[38], residential fuel loads range from 0.3 to 9 gm/cm^2. For city centers, 6gm/cm^2 of floor space in office buildings[39] of 4 and 20 stories covering 40% of the land area give 10 and 50 gm/cm^2 respectively. As for the number of fires the criteria demand,[21] 30 buildings to the 1/5 kilometer city block give about 1000 buildings in the 1.3Km^2 area required. Half of these on fire total 500 fires, which we take as the number of fires necessary for the minimum firestorm. A differing set of criteria[8] gives the same number.

Large-area-fire theory[11] gives 34m/s (76mph) winds into the periphery of both a 10gm/cm^2 area with 18m (6 story) flames and a 50gm/cm^2 area with 90m (30 story) flames. Such powerful inward winds would prevent the firestorm from spreading. An incendiary attack strategist, however, could begin by igniting a very high density of fires in the 1.3Km^2 minimum area. This would start a firestorm, or "seed storm," to generate the 34m/s winds. He could then spot a ring of "feeder fires" nearby and allow the seed storm wind to spread each feeder fire to some of the buildings between it and the firestorm. The swath of buildings burned between each feeder fire and the seed storm would widen as it approached the seed storm, because of slight shifts in firestorm wind direction. This strategy would greatly enlarge the seed storm with very few additional fires. He could then enlarge the enlarged firestorm with a subsequent ring of feeder fires, and so on. Observation satellites could provide feedback on the fire development. We assume that in this way each laser initiated building fire would spread to 100 unburned buildings. Only 2500 laser initiated fires then would generate a firestorm to burn everything in a 250Km^2 area.

CLIMATIC EFFECTS

This is the area that 1MT of nuclear explosives would burn. The initial nuclear winter study[13] shows that 100MT could burn 25,000Km^2 of the 50,000Km^2 of central city area in the US, Russia, NATO, and former Warsaw Pact. This would generate 130Tg of smoke (assuming 20gm/cm^2 average fuel density) and would initiate a climatic perturbation as disastrous as the 225Tg from the baseline nuclear exchange.

Subsequent refinements[13,14,15,16,17,18,40] of nuclear winter show the amount of smoke for a baseline exchange decreased to 50680Tg, but show movement in other parameters compensating to give a nuclear winter comparable to the initial study. The threshold for a disastrous climatic perturbation is probably below 15Tg. This would give[15,16,17,40] at least a 5°C drop in average continental temperatures, which would give freezes in midlatitude summer. Such freezes would cause massive crop destruction[19,20] and massive human starvation.[+] The central city fuel density has come down also, but not as much. Assuming half that of the initial study, 10gm/cm^2, we obtain 65Tg of smoke from the above 100MT, 25,000km^2 central city attack. We adopt the 65Tg as a

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[+] A critic felt that a 5°C average drop could not be disastrous because it would not likely cause summer freezes and would only shorten the growing season somewhat. Our cited references, however, predict that such freezes would indeed occur. Plants unprepared for freezing by the usually gradually decreasing temperatures through the Fall season die when hit with a freeze. A 5°C average temperature drop compounded by what would have been a normally cool fluctuation in summer weather further compounded by the patches of concentrations of nuclear winter smoke reducing the local temperature even further is predicted to produce freezes. Thereby, the continents would be "strafed" by moving patches of smoke concentration killing the vegetation under them. With enough "strafing" vegetation over most of the continental interiors would be destroyed.

"full-scale" nuclear winter.[**] Also, for illustrative purposes, we let 65Tg of smoke be the equivalent of 100MT of nuclear explosives, although the relationship is not very linear.

The above smoke amounts for full scale and the threshold winters are conservative assumptions since they assume much suburban fire and few firestorms. A laser attack would give smoke of the higher absorption[16] typical of central cities and give smoke deposited at higher altitudes (corresponding to 100% from firestorms) where its removal rate from the atmosphere is much slower. A firestorm burning 4gm/cm^{2} over 2 hours gives a smoke plume with a large tail into the stratosphere.[18] The 10650gm/cm^{2} of the city centers would give even higher deposition.

From figures presented in the previous section then, it follows that the number of laser ignited building fires required for the adopted full-scale winter would be 0.25x10^{6}. To check this figure another way, consider that there are over 100 cores of cities of over 10^{6} in population in the US, Russia, NATO, and former Warsaw Pack, and over 700 of over 10^{5} in population. Burning all of the former plus half of the latter would require 400 seeds at 500 fires/seed plus 25,000km^{2} at 8 fires/Km^{2} (1% of the buildings on fire) to total 0.4x10^{6} fires, which is in reasonable agreement with the above figure.

RESULTS FOR THE ORBITING CHEMICAL LASER

These 0.25x10^{6} fires required for 65Tg of smoke happen to equal the 0.25x10^{6} building fires available from the BMD in the above two examples. This shows the chemical laser boost phase BMD to be capable of a climatic perturbation comparable to that reported in the original nuclear winter paper.[13] This occurs under the very conservative combinations of attack angle and atmospheric transmission used in the examples. Results displayed in **Table I** and Figure **Table I** show that these are indeed conservative figures. The 0.25x10^{6} fires

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[**] A reviewer criticized these arguments as inconsistent because the updated figures give 65Tg from the central city attack while the baseline attack, which includes the central city attack and much more, gives about the same 50680Tg. The early figures indicate that the central cities would contribute 130Tg/225Tg=60% of the smoke. The later figures, using the high end of the later baseline exchange smoke, gives the central cities contributing 65Tg/80Tg=80% of the smoke. This is consistent with the fact that the central city fuel load estimates decreased with time much less than other areas. Even through, the lower end of the later baseline estimate, 50Tg, obviously would give an absurd comparison. However, all of these figures come from different authors estimating uncertain guantities. Dividing the opposite ends of the error bars for two such quantities might easily be expected to give absurdities. Furthermore, a reduction of the central city smoke to 80%×50Tg=40Tg reveals, upon examination of our results, no significant alteration of the conclusions of this paper.

require 22.5x10^6 shots, and up to 5 times this number of shots may be reasonable while the 15Tg threshold for laser winter is 1/15 of this number of shots. The chemical laser BMD may be capable of 75 times the threshold for laser winter.

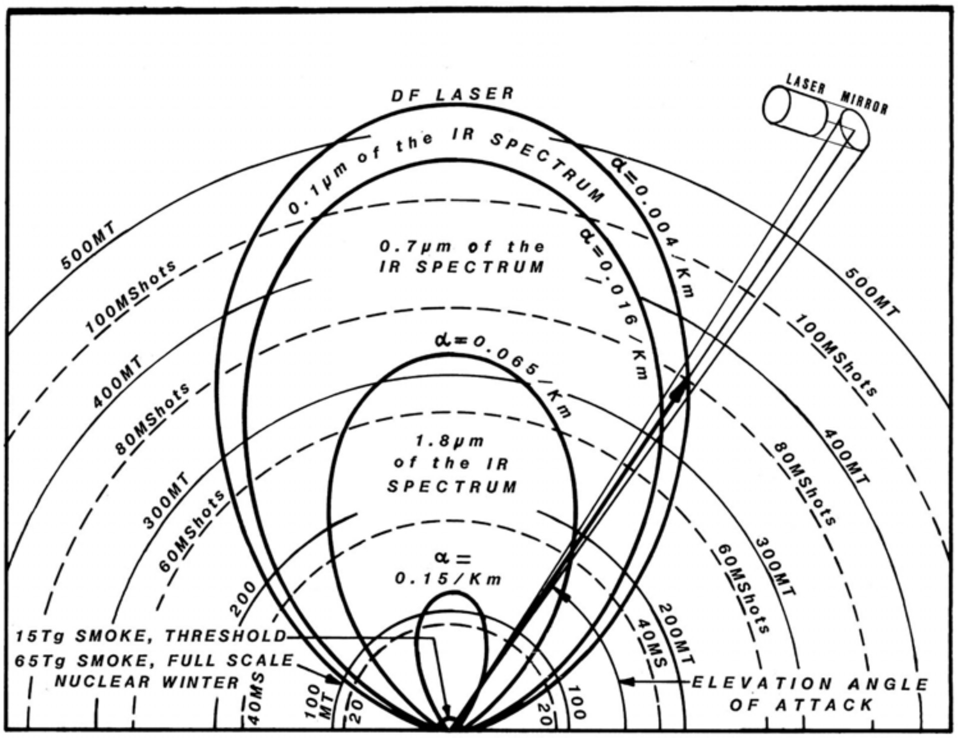

Figure 3. Surface Incendiary Threat from a Space Based Chemical Laser BMD.

Millions of potentially fire initiating laser shots and megatons of nuclear weapon equivalent fire initiating capability versus attack elevation angle for various atmospheric absorption coefficients. Between each pair of curves is a spectral bandwidth figure that gives the amount of the infrared spectrum with atmospheric attenuation coefficients lying between the two curves. The sum of all of these IR bandwidth figures that lie outside the 100 megaton grid line relates directly to the likelihood that a chemical laser would be developed that would threaten a full-scale nuclear winter.

SENSITIVITY

An extensive sensitivity analysis,[24] that varies all but three of the uncertain parameters over all reasonable extremes, gives insignificant changes.

One of the remaining three parameters is the amount of fuel onboard the space-based laser battle stations. If the 150 sec supply were reduced to the mission threshold of 50 sec, this 3-fold change would be insignificant relative to the 75-fold tolerance found above. Furthermore, the nominal BMD we adopted assumed laser phased arrays brighter than most of those proposed. Lessor brightness would greatly increase the energy required per missile kill but leave the energy required per fire the same. Therefore, if our assumed BMD were of the lessor brightness typical of most BMD proposals, the onboard fuel would be increased and the fire capability would be greater yet.

The second untreated parameter is the percentage of the buildings on fire in the "feeder" zone of the firestorm necessary for the spread of the firestorm. If the required percentage were increased from the nominal 1% to as much as 75%, then a threshold climatic perturbation would still not be excluded.

The last and least certain of the untreated parameters is the percentage of laser shots (capable of starting a fire) that actually succeed in setting a building on fire. But reducing the nominal 1/90 by the 75-fold tolerance shows that only 1 success out of every 6750 shots would still give an exceeded climatic threshold. Such an extraordinary fire prevention and fighting capability seems extremely unlikely.[##]

Thus, even if these three parameters are poorly

[##] In addition to the reflective coverings of windows, any number of extreme fire prevention measures might be introduced. For example, as a second layer of window protection a person with a fire extinguisher might be stationed in every room of every building in every central city core. Unfortunately, dealing with a human enemy in a war is very different from dealing with random accidents. In war, for every countermeasure a human can devise a counter countermeasure. In the above example, a laser attack strategist might tire the window sentries by waiting several days before attacking, then attacking at 3AM when many have dosed off. Alternatively, the strategist could strike out-of-the-blue, since every room cannot be guarded permanently. Even without such a counter countermeasure, it seems remote that the thoroughness and personal discipline required of masses of normally undisciplined civilians could ever be sufficient to prevent no more than one in ten thousand shots from starting a fire. Some window sentries will become hot and open a window, faint or panic and run when a fire starts, have a jammed or negligently inspected fire extinguisher, become disgruntled at something and break the windows, abuse drugs while on sentry, and so on. A badly organized or corrupt supervisor of window sentries might neglect some rooms, or even leave some windows open. Another countermeasure might be the blanketing of city centers with smoke screens. Strategies countering that would also materialize; possibly simply waiting for smoke-screen corps to fail to deal completely with wind changes before attacking.

established, margin exists for large error, so this study can conclude the following: The capacity for an orbiting chemical laser system to give a disastrous climatic perturbation is highly probable. The point of decision on the SDI would appear to be, should a trillion dollars and decades of survival time be expended if there is a high probability that a threat comparable to a nuclear exchange would remain?

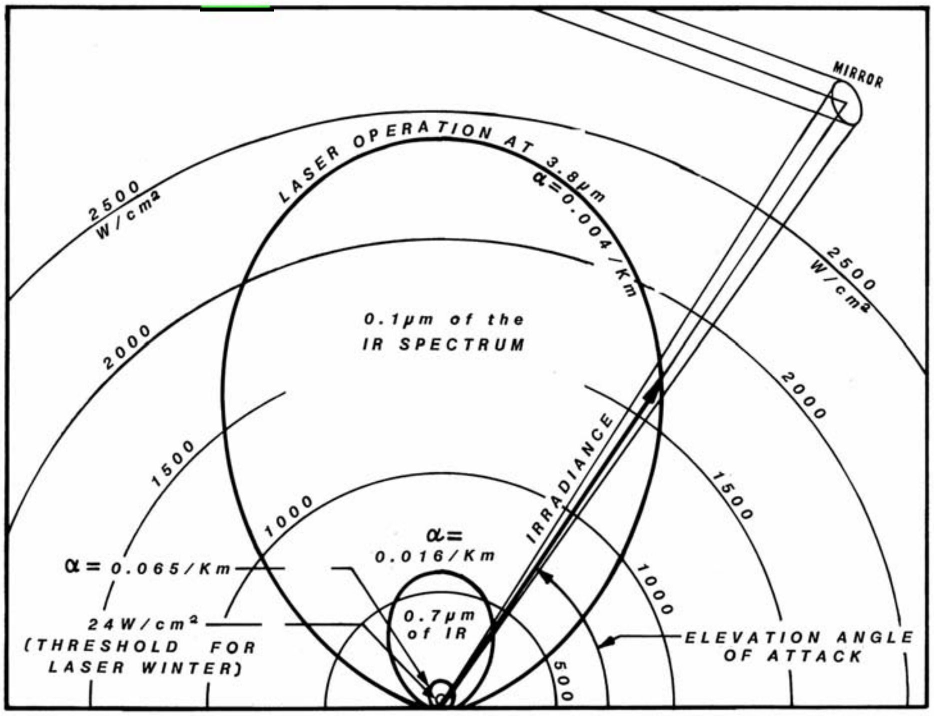

Figure 4. Surface Incendiary Threat from a Ground Based Free Electron Laser BMD.
Ground irradiance versus attack elevation angle for various atmospheric absorption coefficients. Because of unlimited energy availability, nuclear winter effects emerge wherever these curves exceed the 24W/cm^2 curve.

RESULTS FOR THE GROUND-BASED FREE ELECTRON LASER

It can be concluded that a free electron laser system would be even more dangerous. Since it is tunable, designers can choose a highly transmissive wavelength. Since the lasers would be on the ground, their fuel would be essentially unlimited. Thus, under any atmospheric conditions and attack angles in which the lasers can apply much more than the 24W/cm^2 minimum necessary irradiance on the ground, they can initiate essentially an unlimited number of fires and thereby initiate a disastrous climatic perturbation. We find that such a system operating from within 0.1:m around 3.8:m ("$_a$#0.016/Km) could start fires from zenith angles out to 80°. In the visible, a similar evaluation shows that a free electron laser operating at any visible wavelength could start fires from zenith angles out to 65°. Figure **3** shows a 100-fold tolerance within which the system would remain a threat.

CONCLUSION

In conclusion, we can state that a laser boost phase intercept system -- if it actually comes into being by clearing the technological and strategic stability hurdles -- would most likely not only have very significant offensive uses but would itself threaten the very disaster that the SDI is proposed to protect against. It would threaten devastation comparable to a superpower nuclear exchange followed by a disastrous climatic perturbation.

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22. Blooming also deflects the beam. This might complicate targeting for initiating fires on the surface, but the deflection is usually less than a beam diameter. A uniform pointing correction and a variable correction based on estimation of winds might be incorporated.

23. Many somewhat differing system concepts have been proposed and many of the values of the parameters critical to each concept are rather uncertain. To deal with this uncertainty, the approach of this paper is to pick a couple of rather arbitrary but reasonable concepts and then to pick rather arbitrary but reasonable values for their governing parameters. This provides "nominal" systems that can be modeled carefully and in considerable detail to reach a credible conclusion. The uncertainties in the governing parameter values can then be used to establish the confidence level for this conclusion. Critics can argue for different values for the parameters and for their uncertainties. This paper can then be used as a "baseline" from which they can credibly estimate the effects of such changes on the conclusions.

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