Section 3

DIRECTED ENERGY WEAPONS FOR BOOST-PHASE INTERCEPT

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This section describes the entire set of "beam weapons" being considered in the United States today for boost-phase ICBM intercept. Though these weapons receive the most attention, the "kill mechanism" that destroys the booster is not necessarily the most important or technically challenging part of an overall defense system. The next section describes other essential elements of a boost-phase defense.

A revisit to this subject several years from now might well find a new family of directed energy concepts receiving attention. But for now the devices described in this section are the basis for assessments of the prospects for efficient boost-phase defense, in the Defense Department and elsewhere (fig. 3.1). Though some of these concepts are new, many have in fact existed in one form or another for more than twenty years.

Figure 3. I

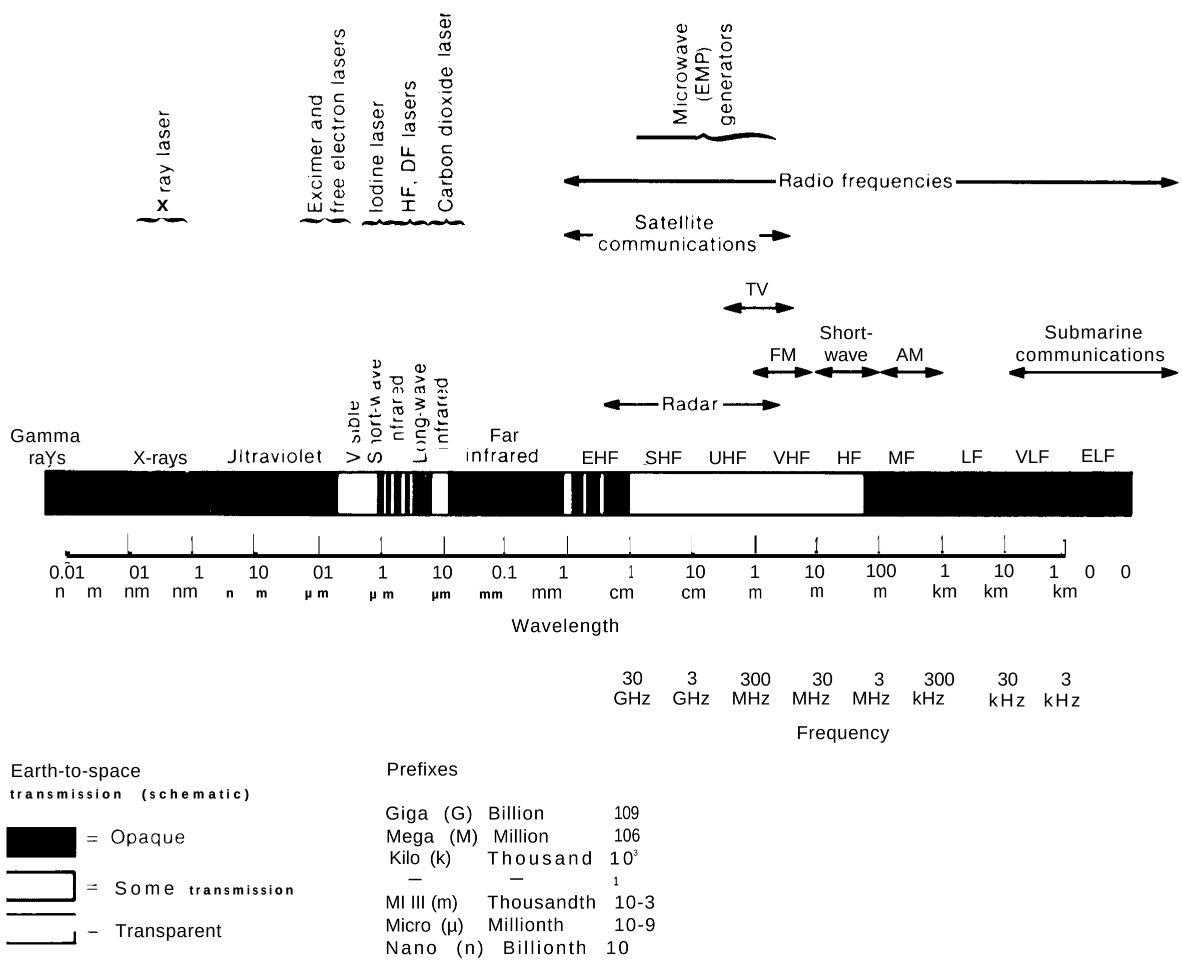


Figure 3.1 **The electromagnetic spectrum, showing spectral regions of interest for directed energy BMD. Particle beams and kinetic energy weapons are not shown because their energy does not consist of electromagnetic radiation, but of atomic and macroscopic matter, respectively. Source: Author**

For each concept this section attempts to work through, with some concreteness, the design of a hypothetical defensive system based on the concept. The resulting designs are **illustrative only;** no significance should be attached to precise numbers. Precision is simply not possible in the current state of technology and study of these concepts.

In all cases, the "current state of technology" (however this is defined in each case) is far from meeting the needs of truly efficient boost-phase intercept. The systems designed in this section illustrate the level to which technology would have to progress to be "in the ballpark." Much attention fastens on the gulf between the current state of technology and the ballpark requirements. This section does not emphasize such comparisons for several reasons. First, in some cases details of the precise status of U.S. research is classified. Second, and more importantly, quantitative comparisons (e.g., "A millionfold increase in brightness is required to fashion a weapon from today's laboratory **device") can mislead** unless accompanied by a deeper explanation of the technology; and the same quantitative measures are not appropriate for all technologies. Third, and most importantly, such comparisons imply that learning how to build the right device is tantamount to developing an efficient missile defense, which is far from true: equally crucial are design of a sensible system architecture, cost, survivability, resilience to countermeasures, and the myriad detailed limitations that do not turn up until later in development.

3.1 SPACE-BASED CHEMICAL LASERS: A FIRST EXAMPLE

This concept of directed energy weapon has been the one most frequently discussed in recent years for boost-phase ICBM intercept. For this reason (and not necessarily because it is the most plausible of all the concepts), it will be used to introduce certain features common to all the schemes that follow.

Making and Directing Laser Beams

A molecule stores energy in vibrations of its constituent atoms with respect to one another, in rotation of the molecule, and in the motions of the atomic electrons. The molecule sheds energy in the form of emitted light when it makes transitions from a higher-energy state to a lower-energy state. Lasing takes place when many molecules are in an upper state and few are in a lower state: one downward transition then stimulates others, which in turn stimulate yet more, and a cascade begins. The result is a powerful beam of light.

Energy must be supplied to the molecules to raise most of them to the upper state. This process is called pumping. In the case of the chemical lasers considered in this section, the pumping energy comes from the chemical reaction that makes the lasant molecules: hydrogen and fluorine react to form hydrogen fluoride (HF) molecules in an upper state. The other requirement for lasing–few molecules in the lower state–is satisfied simply by removing the molecules from the reaction chamber after they have made their transitions to the lower state and replacing them with freshly made upper state molecules. The pumping process is not perfect: not all the pumping energy ends up as laser light. The ratio of pumping energy in to laser energy out is called the efficiency of the laser.

Laser light is special in two respects: its frequency is precise, since all the light comes from the same transition in all the molecules; and the light waves from all the molecules emerge with crests and troughs aligned, since the waves are produced cooperatively. These special features make it possible to focus the laser energy with mirrors into narrow beams characterized by small divergence angles (see fig. 3.2). Nonetheless, there is a limit to the divergence angle that even a perfect laser with perfect mirrors can produce. The divergence angle (in radians) can be no smaller than about 1.2 times the wavelength of the light divided by the diameter of the mirror. Thus a laser with 1 micrometer (=1 micron)

Figure 3.2

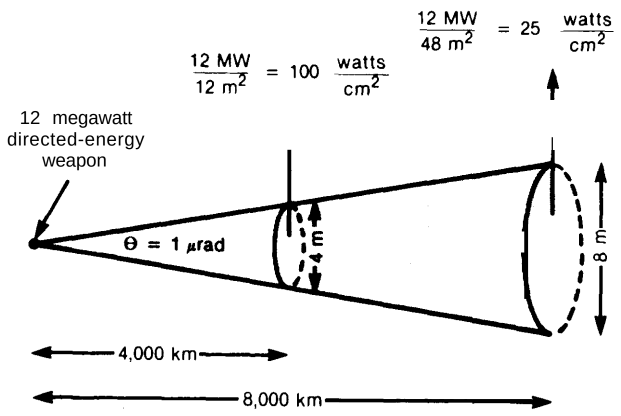


Figure 3.2 Basic power relationships for directed energy weapons. If the directed energy weapon has a divergence angle of 1 microradian, the spot size at a range of 4000 kilometers is 4 meters (12 feet). In this figure, the divergence angle is exaggerated about 1 million times. (For comparison of scale, the Earth's radius is about 6,400 km,) If the directed energy weapon emits 12 megawatts of power, a target within the spot at 4,000 km receives 100 watts on each square centimeter of its surface. (For comparison, 100 watts is the power of a lightbulb, and atypical commercial powerplant produces 1,000 megawatts). Since a watt of power equals one joule of energy per second this weapon would take 10 seconds to apply a kilojoule per square centimeter (1 KJ/cm^2) to the target at 4,000 km range. Source: Author

wavelength projected with a 1 meter mirror could have at best a 1.2 microradian divergence angle, making a spot 1.2 meters wide at a range of 1,000 kilometers (refer to fig. 3.2).[1] This perfect performance is called the diffraction limit. Dividing the laser power output by the size of the cone into which it is directed (cone size is measured in units called steradians; a divergence angle of x radians results in a cone of size $\pi x^2/4$ steradians) yields the laser's "brightness," the basic measure of a weapon's lethality.

Destroying Boosters with Lasers

Assuming a high-energy laser with small divergence angle can be formed, stabilized **so it does** not wave about (jitter), and aimed accurately, what effect will it have on an ICBM booster? No clear answer to this question can be given without more study and testing. Estimates of the hardness achievable with future boosters are probably reliable within a factor of two or three, though estimates of the hardness of current Soviet boosters are probably reliable only to a factor of 10 or so.

Roughly speaking, laser light can damage boosters in two distinct ways. With moderate intensities and relatively long dwell times, the ***la***ser simply burns through the missile skin. This first mechanism is the relevant one for the chemical lasers described in this section. The second mechanism requires very high intensities but perhaps only one short pulse: the high intensity causes an explosion on and near the missile skin, and the shock from the explosion injures the booster. This mechanism, called impulse **kill, is** more complex than thermal kill and is less well understood. it will be discussed in the next section.

Bearing in mind the uncertainties in these estimates, especially the complex interaction of heating with the mechanical strains of boost, the following estimates are probably reliable: A solid-fueled booster can probably absorb without disruption up to about 10 kilojoules per square centimeter (kJ/cm^2) on its skin if a modicum of care is taken in the booster's design to eliminate "Achilles' heels. " This energy fluence would result from 1 second of illumination at 10 kilowatts per square centimeter (kw/cm^2), since one watt equals one joule per second.[2] Applying ablative (heatshield) material to the skin can probably double or triple the lethal fluence required. Applying a mirrored reflective coating to the booster is probably not a good idea, since abrasion during boost could cause it to lose its lustre. Spinning the booster triples its hardness, since a given spot on the side of the booster is then only illuminated about a third of the time.[3] On the other

[1] The spot from a perfect laser with perfect mirrors would actually be brighter at the center than at the edges. The full angle subtended by this spot (the Airy disk from null to null in the diffraction pattern), is 2.4 times the wavelength divided by the mirror diameter, but most of the energy is in the central fourth of this area: hence the use in the text of the multiplier 1.2.

[2] The lethal fluence (in kJ/cm^2) must accumulate **over a** relatively short time, so that the booster wall suffers a high rate of heating, Thus a flux of 30 watts/cm^2 would deposit 10 kJ/cm^2 in 330 sec of dwell time, but such a slow rate of heating would probably not damage the booster.

[3] It is possible that uniform heating around the circu reference of the booster introduces lethal mechanisms distinct from those that apply to heating a single spot on the side of the booster. In that case, spinning the booster might not lengthen the required dwell time by the full amount dictated by geometry.

hand, currently deployed boosters, especially the large liquid Soviet SS-18s and SS-19s, might be vulnerable to I kJ/cm[2] or even less. These too could be hardened by applying heatshield material.

An Orbiting Chemical Laser Defense System

Consider a space-based BMD system comprised of 20-megawatt HF chemical lasers with 10 meter mirrors. The HF laser wavelength of 2.7 microns is attenuated as it propagates down into the atmosphere, but most of the light gets down to 10 km or so altitude. Deeper penetration is not really needed, since the laser would probably not be ready to attack ICBMs until after they had climbed to this altitude, and in any event clouds could obscure the booster below about 10 km. (Substituting the heavier and more expensive deuterium, an isotope of hydrogen, to make a DF laser at 3.8 micron wavelength would alleviate attenuation, but the longer wavelength would require larger mirrors.)

A perfect 10 meter mirror with a perfect HF laser beam yields 0.32 microradian divergence angle. The spot from the laser would be 1.3 meters (4,0 ft) in diameter at 4 megameters (4,000 kilometers) range. 20 megawatts distributed evenly over this spot would be an energy flux of 1.5 kw/cm[2]. The spot would need to dwell on the target for 6.6 seconds to deposit the nominal lethal fluence of 10 kJ/cm[2]. At 2 megameters (Mm) range, booster destruction would require only a fourth of this time, or 1.7 seconds of illumination. Since light takes about a hundredth of a second to travel 4 megameters and the booster is traveling a few kilometers per second, the booster moves about sO meters in the time it takes the laser light to reach it. The laser beam must therefore lead the target by this distance.

The next step is to choose orbits for the satellites so that the U.S.S.R.'s ICBM silos are covered at all times and so that there are enough satellites overhead to handle all 1,400 of the present Soviet booster population. Equatorial orbits (fig. 3.3) give no coverage of the northern latitudes where Soviet ICBMs are deployed. Polar orbits give good coverage of northern latitudes but concentrate satellites wastefully at the poles where there are no ICBMs. The optimum constellation consists

Figure 3.3

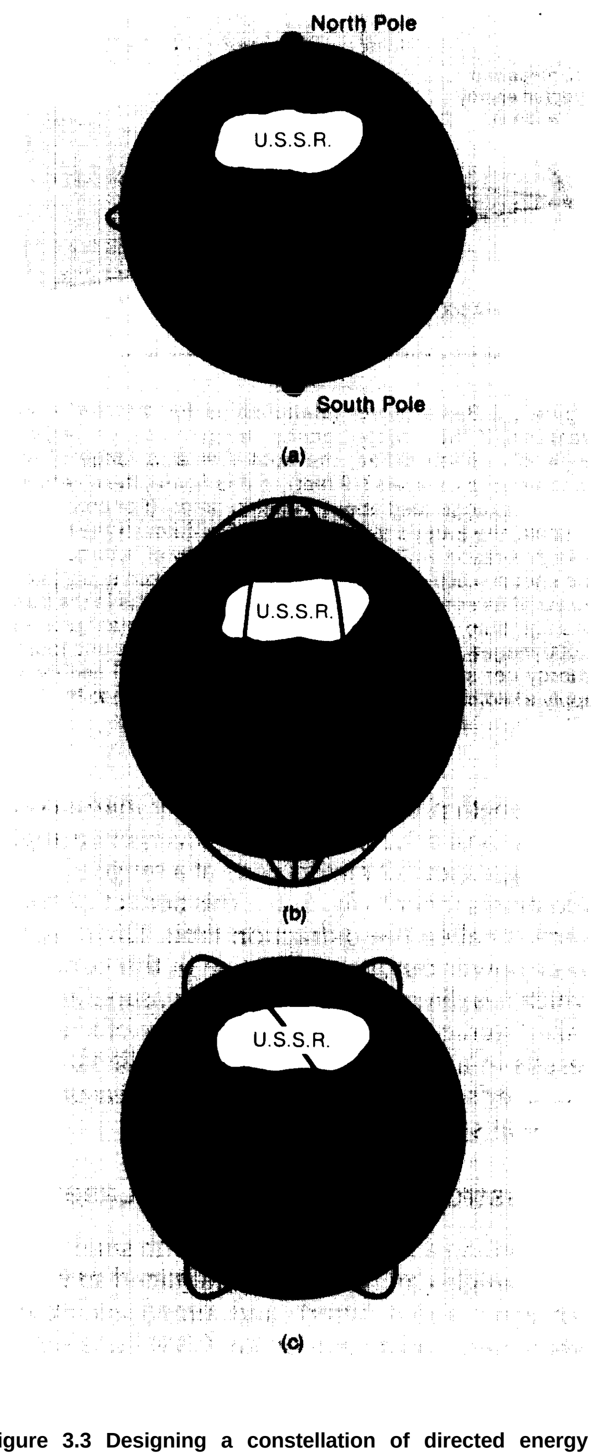


Figure 3.3 Designing a constellation of directed energy weapon satellites for optimum coverage of Soviet ICBM fields. Equatorial orbits (a) give no coverage of northern latitudes. Polar orbits (b) concentrate coverage at the north pole. Inclined orbits (c) are more economical. Slight additional economies are possible in some cases with further elaboration of the constellation design. Source: Author

of a number of orbital planes inclined about 70° to the equator, each containing several satellites.

The shorter the lethal range of the directed energy weapon, the lower and more numerous the satellites must be. For instance, with a lethal range of 3 Mm, 5 planes containing 8 satellites each, or a total of 40 satellites, are needed to ensure that Soviet boosters exiting Soviet airspace would be within lethal range of one satellite. If the lethal range is increased to 6 Mm, only 3 planes of 5 satellites each are needed. This dependence of constellation size on weapon range is displayed in figure 3.4. (It is possible to adjust these numbers a bit by using slightly elliptical orbits with apogees over the northern hemisphere, adjusting inclinations and phasing, etc.). In the present example, requiring that at least one HF laser be no further than 4 Mm from each Soviet ICBM site at all times (corresponding to no longer than 6.6 seconds dwell time per booster) results in the illustrative constellation of 32 orbital positions shown in figure 3.5.

Since the 1,400 Soviet boosters currently deployed are spread out over most of the Soviet Union, perhaps 3 of the 32 orbital positions would be over or near the Soviet Union at a time, able to make efficient intercepts. That is, only one in 11 deployed U.S. battle stations would participate in a defensive engagement. The ratio of the total number of battle stations on orbit to the number in position to participate **in a defensive engagement is called the absentee ratio.** The inevitable waste reflected in the absentee ratio—

Figure 3.4

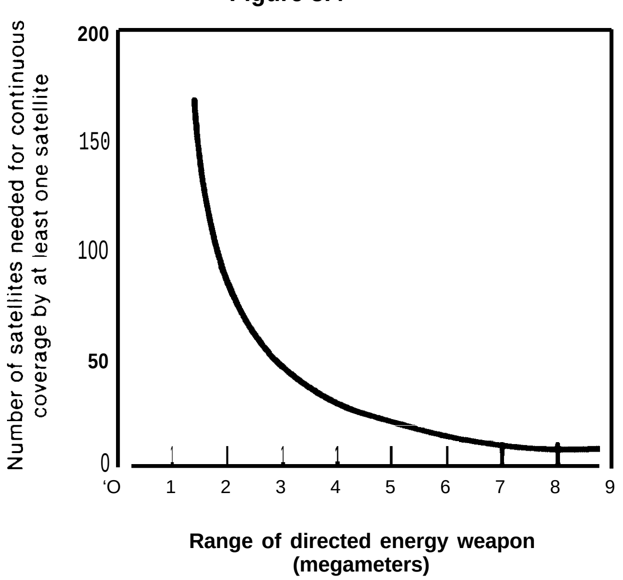


Figure 3.4 The number of satellites needed in a constellation to ensure that at least one satellite is over each Soviet ICBM field at all times depends on the effective range of the directed energy weapon. For every one defensive weapon required overhead a Soviet ICBM field to defend against a rapid Soviet attack, an entire constellation must be maintained on orbit. Since there are many Soviet ICBM fields distributed over much of the Soviet landmass, more than one satellite in each constellation would be in position to participate in a defensive engagement. The ratio of the number of satellites in the constellation to the number over or within range of Soviet ICBM fields is called the absentee ratio. If all Soviet ICBMs were deployed in one relatively small region of the U. S. S. R., the absentee ratio would be the same as the number of satellites in the constellation. Source: Author

Figure 3.5

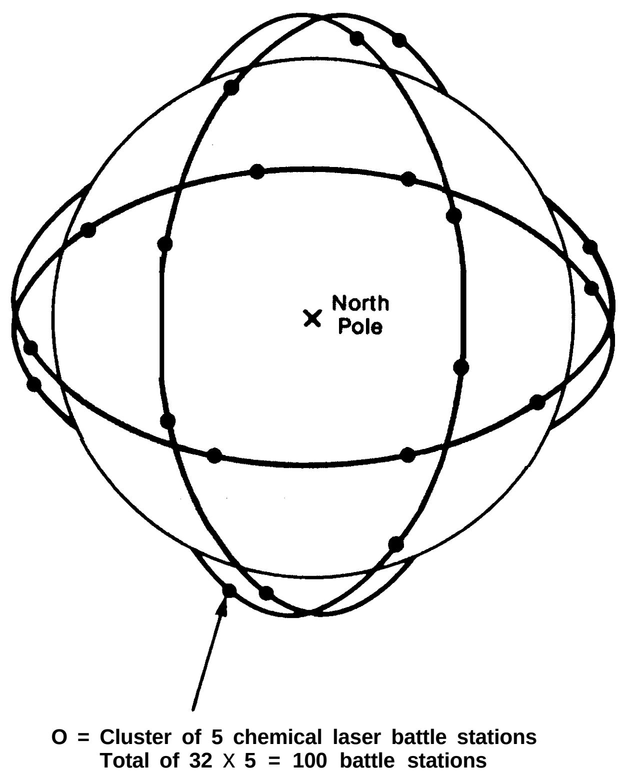


Figure 3.5 Constellation of hypothetical directed energy weapon satellites with 4,000 km range. The orbits are circular with 1000 km altitude. Each of the four orbital planes consists of eight positions spaced 45° apart around the circle. In the example given in the text, five chemical laser battle stations are clustered at each point shown in this figure, for a total of 32 x 5 = 160 battle stations. Source: Author

usually on the order of 10—offsets an oft-cited theoretical advantage of boost-phase intercept, namely, that intercepting one booster saves buying 10 interceptors for the booster's 10 RVS. On the other hand, coverage of the U.S.S.R.'s ICBM fields automatically gives good coverage of essentially all submarine deployment areas. Obviously the absentee ratio would be 32—the full constellation size—and not 32/3 = 10.7 if Soviet ICBM silos were not spread out so widely over Soviet territory but were deployed over a third or less of the Soviet landmass, so that only one of the 32 U.S. satellites was within range.

Three of the earlier described laser satellites in position over the Soviet ICBM fields are not enough to intercept 1,400 boosters if all or most of the boosters are launched simultaneously. Each satellite can only handle a few boosters because it must dwell for a time on each one. The time a chemical laser must devote to each booster depends on the satellite's position at the moment of attack—6.6 seconds for 4 Mm range, 1.7 seconds for 2 Mm range, etc. Taking 2 Mm as an average range for the 32-satellite constellation (hoping the Soviets do not choose a moment when most of the U.S. satellites are farther than 2 Mm from the ICBM flyout corridors to launch all their boosters simultaneously), a laser must devote an average of 1.7 seconds to each booster.

If the boosters in the future Soviet arsenal resemble the U.S. MX, and the defense waits 30 seconds or so to confirm warning and to wait for the boosters to climb to an altitude where the HF laser can reach, each booster is accessible for 150 seconds of its 180 second burn time. Each laser can therefore handle no more than 90 boosters, even with instant dewing of the beam from target to target. If 1,400 Soviet boosters were launched simultaneously, (1 ,400)/(90) ≅ 15 lasers would be needed in position, for a worldwide total (multiplying by the absentee ratio) of (10.7) X (15) = 160 satellites.

If the Soviets doubled their arsenal to 2,800 boosters, the United States would need to deploy another 160 satellites, possibly an uncomfortable cost trade for the United States.

What is worse, if the Soviets deployed 1,400 missiles in a single region of the U.S.S.R. (at a U.S.-estimated cost of $21 billion for Midgetman-like ICBMs; see section 2 above), the US would have to build, launch, and maintain on orbit an additional (32) X(1 400)/(90) ≅ 500 lasers plus their fuel and support equipment.

If Soviet boosters were covered with shielding material and spun during flight to achieve an effective hardness of, say, 60 kJ/cm^2, a laser would have to devote 10 seconds to each booster at 2 Mm range, requiring a sixfold increase in the number of satellites, to 960. Alternatively, the average range of each engagement could be reduced to keep the dwell time at 1.7 seconds, with corresponding increase in constellation density (fig. 3.4). Either way, the number of U.S. satellites would grow to nearly the number of Soviet boosters intercepted.

Table 3.1.—Variation of the Number of Chemical Laser Battle Stations Needed to Handle a Simultaneous Launch of Soviet ICBMs, Depending on Characteristics of the Soviet Arsenal and the U.S. Laser Defense

Departure from baseline	Number of Soviet boosters	Booster characteristics	Geographic distribution	Hardness (kJ/cm^2)	Laser power (MW) and aperture diameter (m)	Approximate number of battle stations needed
Baseline	1,400	MX-like	Current Soviet	10	20/10	160
Booster number	2,800	MX-like	Current Soviet	10	20/10	320
Deployment geography	1,400	MX-like	One region	10	20/10	500
Booster hardness	1,400	MX-like	Current Soviet	60	20/10	960
Laser brightness	1,400	MX-like	Current Soviet	10	80/50 (100 times brighter)	20-30
Booster burn time	1,400	Fast-burn	Current Soviet	10	20/10	800-1,600
Booster burn time	1,400	SS-18-like	Current Soviet	10	20/10	90

SOURCE: Author.

If the United States developed a battle station 100 times brighter (using, say, a 80 MW laser with an effective mirror diameter of 50 meters), a few lasers overhead (20 to 30 total worldwide) could easily handle an attack of 1400 boosters hardened to 10 kJ/cm^2. If the boosters were hardened to 60 kj/cm^2, over 100 such lasers would be needed.

Deployment by the Soviets of 1400 fast-burn boosters would give the U.S. lasers just 20 to 40 seconds, rather than 200 seconds, to destroy all the boosters. The U.S. constellation would consequently need to grow by a factor 5 to 10, to 800 to 1600 satellites!

Table 3.1 summarizes how the size of the defensive deployment varies with the parameters assumed.

Requirements for a Chemical Laser Defense

Figure 3.6 displays the performance of various hypothetical HF lasers. Keeping the size of the battle station constellation down to a hundred rather than several hundred satellites means lethal ranges of at least 4 Mm with illumination times less than about 1 second, assuming the defense must be capable of intercepting 1,000 to 2,000 Soviet boosters with launches timed to keep the boosters as far from the U.S. lasers as possible. Further assuming Soviet booster hardening to at least 10 kJ/cm^2 results in a requirement for chemical lasers considerably brighter than the 20 MW, 10-meter laser described above. A hundredfold increase in brightness would be achieved by a laser with power 80 MW and effective mirror diameter 50 meters.

Such a laser would be about 10 million times brighter than the carbon dioxide laser on the Air Force's Airborne Laser Laboratory. The current Alpha laser program of the Defense Advanced Research Projects Agency (DARPA) aims at a construction of an HF laser of just a few megawatts and built only for ground operation. Nonetheless, there is no fundamental technical reason why extremely bright chemical lasers cannot be built. In theory, several lasers can be operated together so that the brightness of the resulting beam increases with the square of the number

Figure 3.6

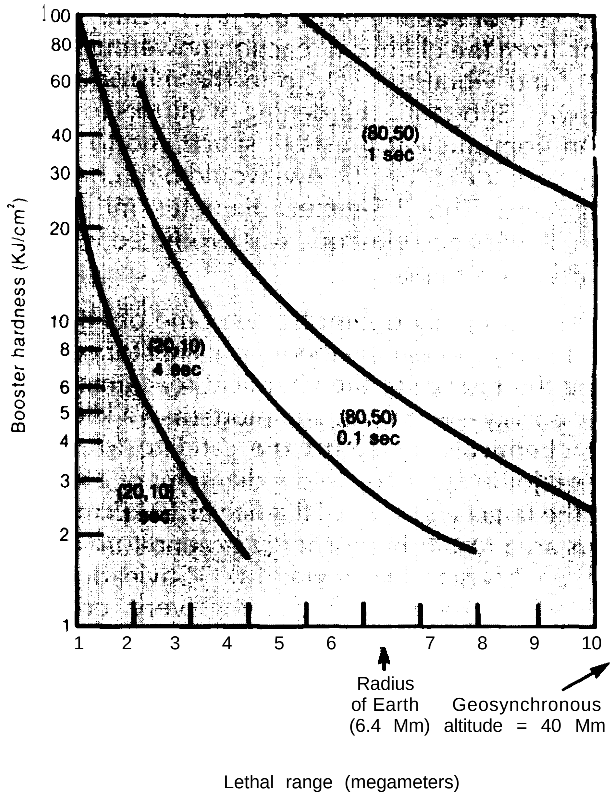


Figure 3.6 Lethal range versus booster hardness for HF chemical lasers of various sizes and dwell times. The labels on the curves have the format (laser power in megawatts, mirror diameter in meters) followed by the amount of time the laser devotes to destroying each booster. Source; Author

of lasers: 10 lasers combined in this way would produce a beam 100 times brighter than each individual laser. The trick is to arrange for the troughs and crests of the light waves from all the lasers to coincide. This theoretical prospect is unlikely to be realized with H F lasers, since their light is actually emitted at several wavelengths and with shifting patterns of crests and troughs.

To yield diffraction-limited divergence, the mirror surface must be machined to within a fraction of a wavelength of its ideal design shape over its entire surface. Since the mirror is over a million wavelengths across, avoiding small figure errors is a severe requirement. A number of small mirrors can obviously combine to produce one large optical surface if their positions are all aligned to within a fraction of a wavelength. The mirrors must maintain perfect surface shape in the face of heating from the laser beam, vibration from the chemical reaction powering the laser, and vibrations set up in the mirror as it is slewed. Substantial hardening of mirrors to radiation from nuclear bursts in space and to the x-ray laser (described below) would be a challenging task. The 2.5-meter diameter mirror on NASA's Space Telescope was produced without these constraints.

An extremely optimistic outcome of HF laser technology—near the theoretical limit for converting the energy of the chemical reactants to laser energy—would require more than a kilogram of chemicals on board the satellite for every megajoule radiated. A spot diameter of 2 meters at the target and a lethal fluence of 10 kJ/cm^2 over this area results in an energy expenditure of 300 MJ per booster. Destroying 1,000 Soviet boosters therefore requires, reckoning very crudely, 300,000 kg of chemicals in position over the Soviet ICBM field, or perhaps 10 million kg on orbit worldwide. The space shuttle can carry a payload of about 15,000 kg to the orbits where the satellite battle stations would be deployed. About 670 shuttle loads would therefore be needed for chemicals, with perhaps another half as many for the spacecraft structures, the lasers and mirrors, construction and deployment equipment, and sensors. 1,000 shuttle missions for every 1,000 Soviet boosters (perhaps Midgetmen) deployed in reaction to the U.S. defense is an impractical competition for the United States. Use of H F chemical lasers for BMD therefore requires remarkably cheap heavy-lift space launch capability in the United States.

The remaining components of the chemical laser defense system—sensors, aiming and pointing technology, and communications— are for the most part generic to all directed energy weapons and are discussed in section 4. Section 5 presents countermeasures the Soviets might take to offset or nullify a chemical laser defense.

3.2 GROUND-BASED LASERS WITH SPACE-BASED MIRRORS

A slight variant of the previous concept puts the laser on the ground and mirrors in space, reflecting the light back down toward Earth to attack ascending boosters. This scheme avoids placing the laser and its power supply in space, though mirrors, aiming equipment, and sensors remain. The excimer and free-electron lasers considered for this scheme are in fact likely to be rather cumbersome, so ground basing them might be the only practical way to use them for BMD. The lasers would emit at visible or ultraviolet wavelengths about ten times shorter than the near-infrared wavelengths of the HF and DF chemical lasers in the space-based concept. Shorter wavelengths permit use of smaller (though more finely machined) mirrors. The high power available with ground basing suggests at least the possibility of impulse rather than thermal kill of boosters.

The term excimer is a contraction of "excited dimer." A dimer is a molecule consisting of two atoms. The dimers considered for these lasers contain an atom of noble gas and a halogen atom, making dimers like xenon fluoride (XeF), xenon chloride (XeCl), and krypton fluoride (KrF). The laser light comes from dimers in an excited upper state decaying to a lower state, just like in the HF laser. Excimer lasers tend to emit light in pulses rather than in a continuous wave. The population of upper-state molecules is provided by pumping with electric discharges in a rather complicated process. The population of lower-state molecules remains small because the lower-state dimer is unstable and quickly breaks up into its two constituent atoms. The pumping process for excimer lasers is inefficient, so only a small fraction of the energy put into the laser in the electric discharge emerges as laser light. Powerful excimer lasers would therefore be large and would need to vent large amounts of wasted energy; these characteristics make them unsuitable for space basing. Development of excimer lasers is at an early stage, and no excimer lasers exist with anything remotely approaching the characteristics needed for this boost phase intercept concept.

Figure 3.7

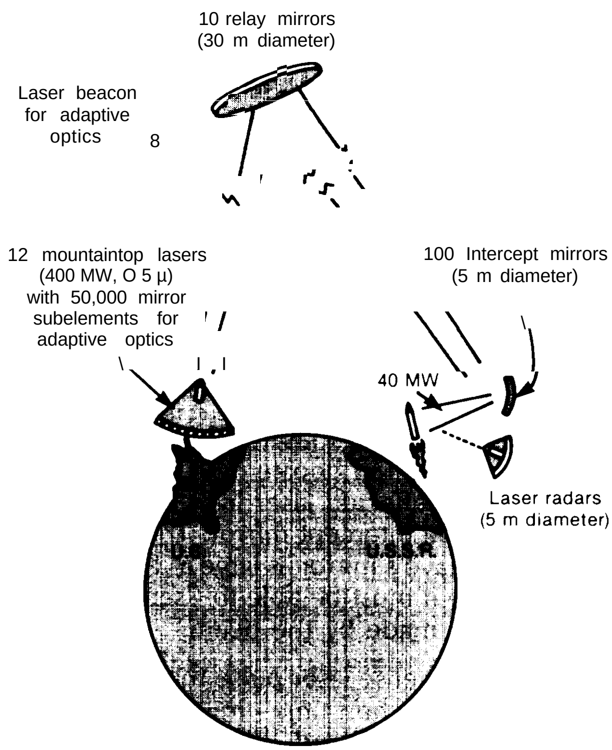


Figure 3.7 Illustrative configuration of ground-based excimer or free-electron laser and space-based mirrors for thermal kill of Soviet ICBM boosters. **Source: Author**

Power outputs achieved in the laboratory are still several orders of magnitude less than the average power needed for thermal kill, and the energy achieved in a single pulse is much smaller than the single-pulse energies needed for impulse kill.

The working of a free-electron laser (FEL) is more complicated.[4] As the name suggests, the light-emitter (lasant) is free electrons emitted from particle accelerator. Pumping therefore orignates in the electrical source powering the accelerator. The free electrons from the accelerator are directed into a tube called the wiggler that has magnets positioned along its length. The magnets cause the electrons to wiggle back and forth as they transit the tube. As they wiggle, the electrons emit some of their energy as light. The presence of light from one electron causes others to emit in the usual cooperative manner of a laser, and a cascade begins. By adjusting the positions of the magnets and the energy of the electrons, the wavelength of the light can be tuned to any value desired. The only advantage of the FEL over excimer lasers is the high efficiency that can (theoretically) be obtained with the former. It has been suggested that it might even be possible to position FELs in space like HF chemical lasers. FEL operation at visible wavelengths is in its infancy, and the experimental devices used are many millions of times less powerful than those required in this BMD.

The BMD scheme calls for a large ground based excimer or free electron laser, relay mirrors at high altitude to carry the laser beam around the curve of the Earth, and intercept mirrors to focus the beams on individual boosters (fig. 3.7). The characteristics of a nominal system for thermal booster kill are easily ascertained. Suppose first that there are enough intercept mirrors so that the average range from mirror to booster is 4 Mm, and suppose the Soviet boosters are destroyed with 10 kJ/cm^2 deposited on a spot as small as several centimeters wide. Assume the excimer or free electron laser operates at about 0.5 microns, in the visible band. Then a 5 m intercept mirror will produce a spot 50 cm wide at 4 Mm range. If a half second of the main laser beam is devoted to each booster, then the required 10 kJ/cm^2 will be accumulated if the power reflected from each intercept mirror is 40 MW.

Only about a tenth of the power emitted by the ground based laser in the United States would be focused on the booster over the U.S.S.R. The remainder would be lost in transit through the atmosphere and in reflection from the two mirrors. Thus a 400 MW laser is required.

Passage through the atmosphere poses a number of problems for the primary laser beam. The most important source of interference is turbulence in the air, causing different parts of the laser beam to pass through different optical environments when exiting the atmosphere. Each part of the beam suffers a slightly different disruption, and the beam that emerges does not have the

[4] See Charles A. Brau, "Free Electron Laser: A Review, " *Laser Focus,* March 1981; *Physics Today,* December 1983, p. 17.

orderly arrangement of crests and troughs needed for diffraction-limited focusing from the intercept mirror. Without compensation for atmospheric turbulence, the ground-based laser scheme is completely impractical. Fortunately, the pattern of turbulence within the laser beam, though constantly changing, remains the same for periods of a few milliseconds. Since it takes only 0.1 millisecond for light to make a round trip through the atmosphere, the effect of turbulence on the laser beam can be compensated for with the following technique, called adaptive optics: A low-power laser beacon is positioned near the relay mirror. A sensor on the ground observes the distortion of the beacon beam as it passes through the atmosphere. The beam from the ground-based laser is then predistorted in just such a way that its passage through the same column of air transited by the beacon beam re-forms it into an undistorted beam.

Figure 3.7 shows the many components required by the ground-based laser concept. Since each Soviet booster requires 0.5 sec of beam at some time during its 200 sec. boost phase, four beams would be needed to handle **1,400** Soviet boosters launched simultaneously (assuming no retargeting delays), The lasers should be deployed on mountain tops to make atmospheric effects manageable, and enough should be deployed that at least four sites are always clear of cloud cover. The mirror on the ground would need to be tens of meters across and divided into tens of thousands of individually adjustable segments for predistortion of the wavefront. Each relay mirror would need to be accompanied by a beacon. Four large interception mirrors would be needed within 4 Mm of each Soviet ICBM flyout corridor, giving a worldwide constellation of a hundred or so.

The small laser wavelength means that all mirrors must be more finely machined than the mirrors for the chemical laser and can tolerate smaller vibrations and stresses due to heating from the laser beam. The small wavelength also results in a spot 10 times smaller at the target than the spot from a chemical laser beam at the same range. This small spot requires pointing accuracy ten times finer. Perhaps most important of all, the plume from the booster motor is too large to serve as target for such a narrow beam. Some way of seeing the actual missile body against the background of the plume is needed for the short-wavelength laser schemes (and for some configurations of chemical lasers). One answer to this problem, described in section 4 below, is to position near each intercept mirror a low-power laser and a telescope (a laser radar or ladar): the laser illuminates the booster and the telescope observes the reflected laser light, directing the pointing of the intercept mirror. The ladar telescope must have a mirror as large as the intercept mirror, since it must be able to “see” a spot as small as that made by the beam.

A single immense laser pulse that deposits 10 kJ/cm^2 in a very short time–millionths of a second rather than a second— might cause impulse kill rather than thermal kill, In impulse kill, the laser pulse vaporizes a small layer of the booster skin and surrounding air. The superheated gases then expand explosively, sending an impulsive shockwave into the booster. A strong enough shockwave might cause the booster skin to tear. The advantage of this kill mechanism is that it would be very difficult to protect boosters from it. The disadvantages are that impulse kill requires prodigious laser pulses and mirrors that can withstand them, and that the mechanism is poorly understood and depends on myriad factors like the altitude of the booster at the moment it is attacked.

3.3 NUCLEAR BOMB-PUMPED X-RAY LASERS: ORBITAL AND POP-UP SYSTEMS

The U.S. Government has revealed efforts at its weapon laboratories to use the energy of a nuclear weapon to power a directed beam of x-rays. Such devices are said to constitute a “third generation” of nuclear weapons, the first two generations being the atomic (fission) and hydrogen (fusion) bombs. Each succeeding generation represented a thousandfold increase i n destructive energy, from a ton of high explosive to a kiloton fission weapon to a megaton fusion weapon. The third generation weapon uses the same amount of energy as the fusion weapon, but directs much of that energy toward the target rather than allowing it to escape in all directions. At the target, therefore, the energy received is much greater than the energy that would be received from a hydrogen bomb at the same range.

x rays lie just beyond ultraviolet light on the electromagnetic spectrum and have wavelengths about a thousand times smaller than visible light (see fig. 3.1). Compared to the infrared, visible, and ultraviolet lasers in the previous sections, the x-ray laser produces much more energy from its bomb pump, but the energy is spread out over a larger cone. The lethal ranges for boosters turn out to be roughly comparable for all these types of directed-energy device. Obviously the x-ray laser delivers all its energy in one pulse, so there is no question of dwell time on the target. Very short-wavelength x-rays penetrate some distance into matter (witness dental and medical x-rays), but the longer-wavelength x-rays produced by a laser device do not penetrate very far into matter or into the atmosphere.

orbiting and ground-based "pop-up" systems have been proposed as ways to make use of the x-ray laser for boost phase BMD. Both of these schemes have attractive features but also serious drawbacks. It could well be that the x-ray laser device, if a powerful one can eventually be built, will be more useful in other strategic roles than boost-phase BMD.

X-Ray Lasers

Little has been revealed about the characteristics of the bomb-pumped x-ray laser being studied by the United States (the so-called Excalibur device), but some general information can be deduced from the laws of physics and, to a lesser extent, from the scientific literature here and in the Soviet Unions

[5]F.V.Bunkin, V. 1. Derzhiev, and S. 1. Yakovlenko, *Soviet Journal of Quantum Electronics 11* (8), August 1981, p. 981. R. C. Elton, R. H. Dixon, and J. F. Seely, *Physics of Quantum Electronics 6* (1 978), p. 243. Michael A.Duguay, /&d., p. 557. G. Chapline and L. Wood, *Physics Today,* June 1975, p. 40.

Figure 3.8

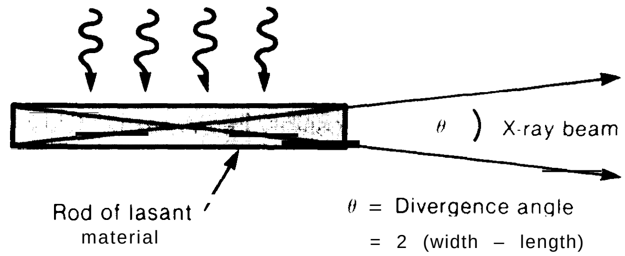


Figure 3.8 In an x-ray laser, a rod of lasant material is pumped to upper energy states by a nuclear bomb. Those cascades of downward transitions that travel lengthwise build up more energy than sideways-going cascades. As a result, most of the energy emerges from the ends of the rod into a cone with divergence angle equal to twice the rod width divided by its length. Source: Author

The pumping source for the x-ray laser is a nuclear bomb. The radiant heat of the born b raises electrons to upper energy levels in atoms of lasant material positioned near the detonation (the chemical nature of the lasant material has not been revealed). As the electrons fall back again to lower levels, it can happen that for a moment many atoms are in a given upper level and few in a lower level; this is the necessary condition for lasing from the upper level to the lower level. The wavelength of the emitted x-ray is determined by the energy levels involved. The wavelength of the laser under study in the United States is classified. We will use a round number of 1 nm.

Since x-rays are not back-reflected by any kind of mirror, there is no way to direct the x-rays into a beam with optics like the visible and infrared lasers. Nonetheless, some direction can be given to the laser energy by forming the lasant material into a long rod. Recall that a laser beam builds up when light from one lasant atom stimulates the upper-to-lower-level transition in another atom, which stimulates a third, and so on. The result is a cascade of light heading in same direction as the light from the original atom. The light pulse gets stronger and stronger as it traverses the lasant medium stimulating more and more transitions. In a long rod of lasant material, cascades that get started heading lengthwise down the rod are highly amplified by the time they leave the rod, whereas sideways-going cascades remain small. The result is that most of the laser energy emerges as a beam aligned along the rod axis (fig. 3.8).

The projected capabilities of the x-ray lasers being studied in the U.S. are classified; but it is fairly easy to determine the upper limit to how powerful such a laser could possibly be. Whether R&D will succeed in making such a perfect laser cannot be said. But it will become clear that something very close to the perfect laser is required for boost phase intercept, though a less successful development would still yield a potent antisatellite weapon.

A l-megaton nuclear weapon releases about 4 billion megajoules of energy. By surrounding the bomb with lasant rods, most of this energy can be harnessed to pump the laser. Since the pumping mechanism for the x-ray laser is rather disorganized and wasteful, like the pumping mechanism for excimer lasers, at most a few percent of the bomb energy can be expected to end up in the laser beam.

The resulting 100 million megajoules or less of laser energy emerges from the rods into cones with relatively large divergence angle. It is easy to see why this divergence angle is much larger than the divergence angle obtained with the mirror-directed lasers treated in the previous section, The divergence angle is determined by the ratio of the width of the rod to its length, as in figure 3.8. A practical length for a rod is no more than about 5 meters. Making the rod thinner decreases the divergence angle, but beyond a certain point no further narrowing of the beam cone is possible. The limit arises from diffraction, just as with the infrared and visible lasers: the divergence angle of light emitted from an aperture (mirror, rod tip, or anywhere else) cannot be less than about 1.2 times the wavelength of the light divided by the diameter of the aperture. A very narrow rod therefore actually aggravates diffraction and produces a wide cone. Making the rod thinner results in no further narrowing of the beam when (1 .2) (wavelength) /(rod width) $\cong$ (2) (rod width)/(rod length). For an x-ray wavelength of 1 nm and a rod length of 5 meters, this equation yields an optimum rod width of 0.06 mm and a minimum achievable (diffraction-limited) divergence angle of 20 microradians.

A 1-megaton bomb-pumped x-ray laser can therefore deposit no more than about 100 million megajoules into a cone no narrower than about 20 microradians. The x-ray pulse from detonating such a perfect laser would deposit about 300 kJ/cm^2 over a spot 200 meters wide at 10 Mm range.

Interaction of X-rays with Matter

X-rays of 1 nm wavelength do not penetrate very far into matter: all the energy from such a laser would be absorbed in the first fraction of a millimeter of the aluminum skin of a missile. This paper-thin layer would explode, sending a shockwave through the missile. Thus the x-ray laser works by impluse kill.

Another consequence of the opacity of matter to x-rays is that the laser beam would not propagate very far into the atmosphere. The altitude to which the beam would penetrate depends on the precise wavelength, which is classified. For the nominal 1 nm wavelength described above, boosters below about 100 km would be quite safe from attack. If the wavelength were much shorter, the x-rays would penetrate lower, reaching perhaps 60 km altitude or so. In what follows, it will be assumed that boosters are safe from x-ray laser attack below about 80 km.

One last consequence of the physics of x-ray interaction with matter is noteworthy. When an atom of matter absorbs an x-ray, it emits an electron. As x-rays are absorbed, it becomes harder and harder to remove successive electrons. Finally further x-rays cannot remove further electrons, and the matter becomes transparent. This phenomenon, called bleaching, means that a strong x-ray laser beam can force its way through a column of air by bleaching the column, but a weak laser beam is completely absorbed. An x-ray laser in the atmosphere might therefore be able to attack an object in space because the beam is intense enough in the vicinity of the laser to bleach the air, whereas an x-ray laser in space could not attack objects within the atmosphere. This fact bodes ill for defensive space-based x-ray lasers attacked by similar lasers (or even weaker ones) launched from the ground by the offense.

As with visible and infrared lasers, the lethality of an x-ray laser is subject to large uncertainties. The proper order of magnitude for the amount of x-ray energy per square centimeter that needs to be deposited on the side of a booster to damage it can be estimated fairly easily. But the actual hardness of a booster would depend on many design details in a way that is not fully understood at this time. A simple calculation indicates that 20 kj/cm^2 is a reasonable number to take for the hardness of a booster. This is about the same as for impulse kill by visible laser. An RV would be harder, and a satellite softer.

Orbital Defense Concept

The "perfect" x-ray laser whose characteristics were deduced above would be capable of intercepting a booster from geosynchronous orbit 40,000 km above the Earth. One laser would be needed for each Soviet booster. At lower altitudes, the rods surrounding the bomb could be gathered into several bundles and each bundle aimed at a different booster. At these lower altitudes, though, the absentee problem means that roughly one x-ray laser device would still need to be placed in orbit for each Soviet booster. Though the x-ray lasers are small and light compared to a chemical laser, the cost tradeoff involved in launching a new laser every time the Soviets deploy a new ICBM is obviously not a tolerable one for the United States.

The x-ray laser can attack the boosters after they have left the protective atmosphere but before burnout. Simultaneous launch of all Soviet boosters is not a problem for x-ray lasers in the way it is a problem for chemical lasers that must dwell on each target before passing on to the next. Fast-burn boosters are likewise not a crippling problem for an orbiting x-ray laser system ***unless*** they burn out before they leave the atmosphere, Other countermeasures, most notably the vulnerability of U.S. orbital x-ray lasers to Soviet x-ray lasers, are treated in section 5.

Pop-Up Defense Concept

The pop-up concept represents an attempt to avoid the one-laser-per-booster cost exchange and the vulnerability associated with basing the lasers in space (though crucial sensors remain space-based even in the pop-up scheme). The small size and light weight of the bomb-pumped lasers makes it possible to consider basing them on the ground and launching them into space upon warning of Soviet booster launch.

Figure 3.9 shows why basing the pop-up lasers in the United States is not practical. During the 200 seconds or so of burn time of a Soviet MX-

Figure 3.9

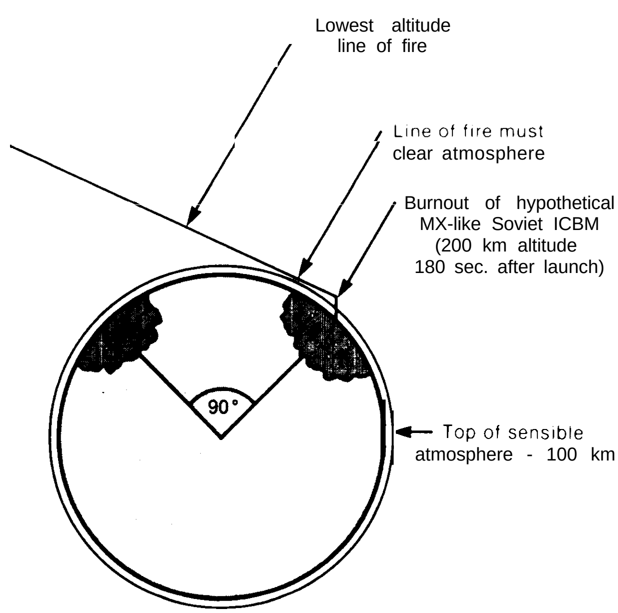


Figure 3.9 X-ray lasers launched from the United States on warning of Soviet ICBM launch would have to climb at least as high **as the line of fire shown in the figure within three minutes to intercept an MX-like Soviet ICBM. Such a huge fast-acceleration defensive booster would be many times larger than the Saturn V that took astronauts to the moon. Source: Author**

[6] A mallet or soft hammer blow applies an impulse per unit area of about 10 ktaps (0.5 kg hammer head, 5 m/see striking velocity, 3 cm radius contact area; 1 tap = 1 dyne-see/cm'). To apply an impulse of this strength to the entire side of an ICBM booster requires a fluence F, whose order of magnitude can be estimated as follows: The cold mass absorption length (a) for 1 nm x-rays is about 0.5 milligrams/cm^2. If all the energy absorbed by the paper-thin absorbing layer were converted to kinetic energy, the boil-off velocity would be (F/a)", meaning an impulse per unit area of order (Fa)$^{1/2}$. 10 ktaps is therefore produced if F =20 kJ/cm^2.

In reality, not all the deposited energy couples to the booster in this way. A more careful calculation of this lessened coupling has been performed by Hans Bethe (private communication).

like ICBM, the U.S.-based pop-up lasers would have to climb high enough to see the Soviet boosters over the Earth's horizon and have a line-of-fire unobstructed by the absorbing atmosphere. Climbing so high so fast requires a booster for the x-ray lasers that is many thousands of times larger than the Saturn V rocket that carried U.S. astronauts to the Moon.

If the British Government allowed the U.S. Government to base x-ray lasers in the United Kingdom, the lasers would be separated from Soviet ICBM silos by only 45 degrees of arc rather than 90 degrees as with U.S. basing. Even so, popping up to attack an MX-like Soviet booster would require an enormous fast-burn booster for the x-ray laser and would put it into position to attack the Soviet booster only seconds before burnout. If the Soviets depressed the trajectory or shortened the burn time of the offensive booster very slightly, or if the United States suffered any delay whatsoever in launching the defensive boosters after Soviet launch (instantaneous warning), this hypothetical U.K.-based system would be useless.

A final possibility would be launch of defensive lasers from submarines stationed immediately off Soviet coasts—in the Kara Sea or Sea of Okhotsk, separated from Soviet silos by about 30 degrees of arc–on SLBM-sized fast-burn boosters. With instantaneous warning, a sea-based laser might be able to climb to firing position a few seconds before burnout of a Soviet MX-like ICBM and would enjoy almost an entire minute of visibility to a slow-burning, high-burnout-altitude booster like the SS-18. Because of the short range, each bomb-pumped laser of the perfect design described above could attack many (over 100) boosters using many individual lasing rods. Such efficiency could well be essential, since a submarine cannot launch all its missiles simultaneously and might only be able to fire one defensive missile in the required few seconds. If the MX-like Soviet boosters were flown on slightly depressed trajections, if warning were not communicated to the submerged submarine promptly, if a human decision to launch defensive missiles were required, or if the Soviets deployed boosters that burned faster than MX, the sub-launched system would be nullified, Last, submarine patrol very near to Soviet shores suggests the possibility of attacking the submarine with shore-based nuclear missiles as soon as its position has been revealed by the first defensive launch. Other countermeasures are discussed in Section 5.

3.4 SPACE-BASED PARTICLE BEAMS

Beams of atomic particles would deposit their energy within the first few centimeters of the target rather than at the very surface as with lasers. The effects of irradiation with the particle beam could be rather complex and subtle and would probably depend on design details of the attacking Soviet booster. The result is uncertainty of several factors of ten in the effective hardness of an ICBM booster to beam weapon irradiation.

Only charged particles can be accelerated to form high-energy beams, but a charged beam would bend uncontrollably in the Earth's magnetic field. (There is one theoretical exception to this statement, described below.) For this reason neutral particle beams, consisting of atomic hydrogen (one electron bound to one proton) deuterium (one electron, one proton, one neutron), tritium (electron, proton, two neutrons) 01 other neutral atoms are considered. To produce a neutral hydrogen (H°) beam, negative hydro gen atoms (H –) with an extra electron are accel erated; the extra electron is removed as the bean-emerges from the accelerator,

Two features of neutral particles beams domi nate their promise as boost phase intercept weap ons (leaving aside entirely the issue of counter measures). The first is the uncertain lethality o the beam. The second is the fact that the bear-r cannot propagate stably through even the thinnest atmosphere and must wait for an attacking booster to reach very high altitude.

Generating Neutral Particle Beams

The accelerator that accelerates the negative hydrogen ion is characterized by its current in amperes, measuring the number of hydrogen ions per second emerging from the accelerator; and by the energy of each accelerated ion in electron volts (eV; 1 eV = 1 watt per ampere). Multiplying the current by the energy gives the power of the beam, so that a l-amp beam of 100 MeV particles carries 100 MW of power. Ground-based high-current accelerators and ground-based high-energy accelerators have been built and are operated daily in laboratories. One of the challenges for neutral particle beams as weapons is that they require both high current and high energy. Another challenge is to provide multi-megawatt power sources and accelerators in a size and weight suitable for space basing.

Magnets focus and steer the beam as it emerges from the accelerator. The last step is to neutralize the beam by passing it through a thin gas where the extra electron is stripped off in glancing collisions with the gas molecules, forming Ho from H-. The divergence angle of the beam is determined by three factors. First, the acceleration process can give the ions a slight transverse motion as well as propelling them forward. Second, the focusing magnets bend low-energy ions more than high-energy ions, so slight differences in energy among the accelerated ions lead to divergence (unless compensated by more complicated bending systems). Third, the glancing collisions that strip off the extra electron give the H atom a sideways motion. This last source of divergence is unavoidable and, by the Heisenberg uncertainty principle, cannot be controlled or compensated. It sets a lower limit on the divergence angle achievable with this method of producing neutral particle beams. Table 3.2 shows the divergence angle resulting from this third source, assuming perfect control of the first two sources. The divergence cone from a neutral particle beam is therefore about 10 times larger than the beam from the chemical laser of section 3.1 and 10 times smaller than from the x-ray laser of section 3.3.

A 100 MeV, 0.5 amp neutral tritium **(T°)** beam thus directs 50 MW of power into a cone of divergence angle 2 microradians, producing a spot 10 meters across at 5 Mm range. A target within this spot receives only 65 watts/cm^2, requiring 1.5 seconds of dwell time to deposit only 100 J/cm^2.

Booster Vulnerability to Particle Beams

As soon as the neutral particle beam hits the target, the remaining electron is stripped off, leaving the energetic proton (or deuteron or triton) penetrating deeply into the target. The proton scatters electrons in its path, giving up a small amount of its energy to the electron in each collision. When it has given up all its energy, it stops. For most of its path, it deposits energy uniformly. Thus if a 100 MeV **To** beam penetrates 4 cm into the propellant in a missile, it deposits about 25 MeV along each cm. Protons penetrate more deeply than tritons of the same energy, and all particles penetrate more deeply as they are given more energy (table 3.3).

Table 3.2.—Neutral Particle Beam Divergence Angle

	H“	T“
100 MeV	3.6 microradians	2.0
500 MeV	1.4	1.0

Divergence angle introduced by stripping electrons from a beam of negative hydrogen or tritium ions to produce a neutral beam This source of divergence is an unavoidable consequence of the Heisenberg uncertainty principle applied to the sudden stripping of the electron If the satellite. based accelerator of the negative tons were absolutely perfect, this amount of divergence would remain

SOURCE Author

Table 3.3.—Penetration Range of Neutral Particle Beams Into Matter (in centimeters)

	H“		To	
	100 MeV	250 MeV	100 MeV	250 MeV
Solid propellant or high explosive (density 1.0 gm/cm^3)	9.5	46.6	4.2	20.2
Aluminum	3.5	17.2	1.6	7.6
Lead	0.8	3.9	0.4	1.7

SOURCE Author

Figure 3.10

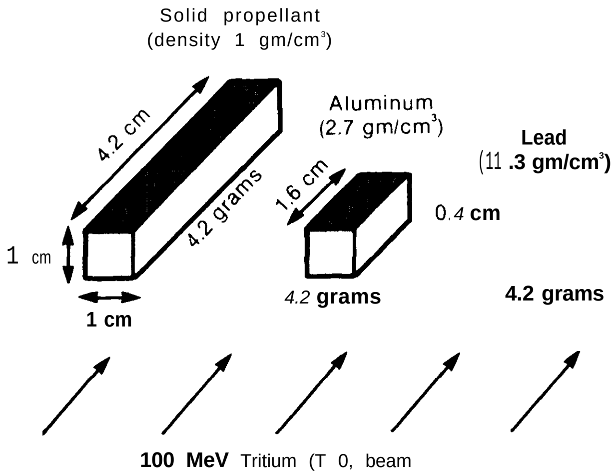


Figure 3.10 A neutral particle beam penetrates farther into an aluminum target than into a lead target but deposits the same energy per gram. Though the energy per gram needed to melt aluminum is well known, the utility of particle beam BMD concepts rests on the less certain destructive effects at lower levels of irradiation. Source: Author

Table 3.4.—Effects of Particle Beam Irradiation

Harmful effect	Energy deposition (Joules per gram)
Disruption of electronics	**0.01 –1 .0**
Destruction of electronics	**10**
Detonation of propellants, high explosive	200
Softening of uranium and plutonium	hundreds
Melting of aluminum.	1,000

Approximate energy deposition (radiation dose) required to produce various harm. ful effects in components of a missile booster and its payload Many other effects, such as melting of glue and plastic and rate-dependent effects, might also be Important

SOURCE Author

The target electrons that recoil from collisions with beam particles eventualy stop, and their energy appears as heat. The 100 MeV T° beam described above, depositing 100 J/cm² on an aluminum target, penetrates to a depth of 1.6 cm. The 1.6 cubic centimeter volume of aluminum **that absorbs this 100 joules** of energy weighs about 4 grams. The **effect** of the **beam is therefore to deposit about** 25 joules per gram throughout the first 1.6 cm of the target. The penetration depth is inversely proportional to the density of the absorbing material, so the same beam on a lead target would not penetrate as far but would **deposit the same energy *per gram* as it** did **in aluminum (fig.** 3.1 O).

The destructive effects of penetrating particle beams are therefore expressed in joules/gram deposited within the target rather than in joules/cm² on the surface of the target as with lasers. Table 3.4 shows the energy deposition needed to produce certain harmful effects. Melting the target is straightforward, but for the other effects at lower levels of irradiation the criteria are less clear. Heat effects in solid booster propellants and in the high explosive and special nuclear materials i n warheads depend on the design of the target. Effects on electronics, particularly transient disruption of computer circuits when electrons are scattered by a passing proton, are poorly known and doubtless quite complicated and specific to the target. Other components not shown in table 3.4 —plastics, glue, guidance sensors–make for a very complicated analysis. What is more, the particle beam might have to suffer the attenuation of passage through, say, two layers of aluminum and a layer of plastic before reach ing a sensitive component.

Uncertainties in the destructive or disruptive effects of small amounts of radiation from a par ticle beam weapon is the principal obstacle to stating what energy, current, and divergent angle would make this concept a candidate for boost-phase intercept.

Shielding to protect components from a neutra particle beam would necessarily be heavy but could still be an attractive countermeasure. It discussed in Section 5.

An Orbiting Neutral Particle Beam System

A critical limitation of neutral particle beam is that they cannot be aimed through even the thinnest atmosphere—air so thin that even the ray laser beam could pass through easily. A neutral beam could not attack a Soviet booster un the booster reached at least 760 km altitude (ve sus about 80 km for the x-ray laser)[7]. Collision

[7]The stripping cross section on oxygen is about 1.5 megabarr Elastic scattering can also be important for beam loss, since the RN scattering angle can be larger than the beam divergence. The auth is Indebted to Dr. George Gull lespe of Physical Dynamics, In in La Jolla for resu Its of his Born approximation cross sectı calculations

between air molecules and H° strip the electron from the H°, and gradually all the remaining protons spiral off the beam axis into 200 km wide circles under the action of the earth's magnetic field.

An MX-like Soviet booster could be attacked between 160 km altitude and burnout at 200 km, a period of about 10 seconds. This short attack window means that the neutral beam cannot afford to dwell for long on each booster.

It is impossible to state with confidence the resilience of an ICBM booster to irradiation with a neutral particle beam. But it is likely that faith would have to be placed in degradation of electronics and other subtle effects, rather than in gross structural damage, for the beam weapon to stand a chance as an economical defense system (ignoring the issue of countermeasures entirely).

Consider again a battle station producing a 0.5 ampere beam of 100 MeV tritium (T°) atoms with 2 microradian divergence. This beam carries 400 watts/cm^2 at 2 megameters range. To do structural damage to the outer few centimeters of a missile's body might take some 2 kJ/cm^2 (depositing 500 J/gin in 1.6 cm depth of aluminum, for instance), requiring 5 seconds of dwell time at this range. Since the available dwell time is only about 10 seconds, each beam could handle only two boosters. With a constellation size of almost 100 for 2 Mm range (fig. 3.4), this kill criterion results in a preposterous system where the U.S. deploys 50 space-based accelerators for every one Soviet booster deployed in one region of the U.S.S.R.

If the assumed Soviet booster hardness is reduced by 100 times, corresponding perhaps to transient upset of unshielded electronics, each satellite can destroy 200 boosters at 2 Mm range, meaning an overall tradeoff of one U.S. accelerator deployed for each two Soviet boosters deployed. Alternatively, the constellation can be thinned out to an effective range of 5 Mm, where each satellite at this range can destroy only 32 boosters but the constellation size is only about 16—still a one-to-two trade of battle stations for Soviet boosters. Such a system scarcely seems promising in terms of cost exchange.

obviously the neutral particle beam would stand no chance of intercepting a fast-burn booster that burns out well within the protective atmosphere. Even an MX-like booster that flew a slightly depressed trajectory would be invulnerable.

A Theoretical Electron Beam System

Physical theory[8] holds out the prospect of one other type of beam besides the neutral particle beam. Under certain circumstances, an electron beam might be able to propagate through the extremely thin air of near-earth space without bending. In this scheme, a laser beam would first remove electrons from air molecules in a thin channel stretching from the battle station to the target, leaving a tube of free electrons and positive ions. The high-energy, high-current electron beam would then be injected into the channel. The beam electrons would quickly repel the free electrons from the channel, leaving the beam propagating down a positively charged tube. The attractive positive charge would prevent the electrons from bending off the beam path under the influence of the geomagnetic field and would also prevent the mutual repulsion of electrons within the beam from causing the beam to diverge. The result would be straight-line propagation to the target, where their effect would be similar in most respects to the neutral particle beam. This scheme will not work for a proton beam.

The physics of intense beam propagation through thin gases is so complex that experiments will be needed to determine whether this concept is even feasible in principle. If so, the concept would resemble the neutral particle beam, with the added requirement for the channel-boring laser and perhaps the ability to intercept boosters at slightly lower altitudes than the neutral counterpart.

8R, B. Miller, *The Physics of Intense Charged Particle Beams*, New York, 1982, ch. 5.

3.5 SPACE-BASED KINETIC ENERGY WEAPONS

Kinetic energy is the name given to the energy of a moving projectile. Use of this term makes ordinary weapons using aimed projectiles into "directed kinetic energy" weapons.

The phenomenology of high-velocity collisions between a projectile and a structure like a booster is surprisingly complex, but in general lethality is not an issue for kinetic energy boost phase intercept concepts. Rather, the problem is getting the projectile from its satellite base to the ascending booster in time to make an intercept. Schemes where the projectile is carried by a small rocket launched from the satellite suffer most directly (leaving aside countermeasures) from a combination of the large number and large size of the rockets needed for adequate coverage. In particular, the most conspicuous public example of the kinetic energy approach, the High Frontier Project's Global Ballistic Missile Defense (GBMD) concept,[9] has extremely limited capability for boost phase intercept of current Soviet ICBMs and would have no capability at all against a future generation of MX-like boosters.

Kinetic Energy Concepts

Rocket attack of ICBM boosters is obviously not as novel as beam attack, but it entails rather more complexity than appears at first blush. The rocket needs radio or other guidance by long-range sensors on its carrier satellite (or other satellites) to direct it to the vicinity of its target, since it is impractical to put a long-range sensor on each rocket. Once in the vicinity of the target booster, the interceptor needs some form of terminal homing sensor and rather sizeable divert rocket motors. Homing on the plume of the ICBM booster is not straightforward, since attacking the plume will obviously not harm the booster: the booster body must be located in relation to the plume. These complications introduce opportunities for offensive countermeasures.

An alternative to rocket propulsion would be to expel the homing vehicles at high velocity from a gun. So-called rail guns use a clever scheme to convert electrical energy to projectile kinetic energy. Since a 10 kilogram projectile ejected with 5 km/see velocity carries 125 megajoules of energy (the amount of energy expended by a 25 megawatt chemical laser in 5 seconds of dwell on a booster), the power requirements of the gun schemes are imposing. Providing chemical fuel or explosives to power a gun therefore involves the same magnitude of on-orbit weight as the chemical laser.

Doing away with the homing sensor and replacing the guided projectile with many small fragments is not an attractive alternative, since the needed fragments end up weighing far **more than the guided projectile.**

The Importance of Projectile Velocity

In the 300 or so seconds from launch to burnout of a slow-burning booster like the SS-18, the defensive rocket or other projectile must fly from its satellite to the path of the booster. Such a booster burns out at about 400 km altitude, so if the projectile wishes to use the entire 300 seconds of boost phase to travel to its quarry, it must make its intercept at 400 km altitude.

Suppose now that the projectile's rocket or gun launcher can give it a maximum velocity of 5 km/see with respect to the carrier satellite. In the 300 seconds of available travel time to its target, the projectile cannot fly more than (5 km/see) **x** (300 see) = 1.5 Mm from its carrier. Each carrier therefore has an effective range of 1.5 Mm (fig. 3.1 la).

Referring to figure 3.4, a constellation of about 240 carrier satellites are needed for continuous coverage of the Soviet Union. Since Soviet ICBMs are spread over much of the country, 10 or so of the carrier satellites might be able to participate in a defensive engagement. The absentee ratio is therefore about 24, The 10 satellites over the U.S.S.R. **at** the moment of a massive Soviet attack need to be able to handle all 1,400 boosters, meaning each satellite needs to carry 140 projectiles.

An idealized rocket accelerating a 15 kg guided projectile to 5 km/see velocity would need to weigh about 80 kg (a real rocket with this capa-

[9] General Daniel O. Graham, *The Non-Nuclear Defense of Cities: The High Frontier Space-Based Defense Against ICBM Attack* (Cambridge: Abt Books, 1983).

Figure 3.1 l(a)

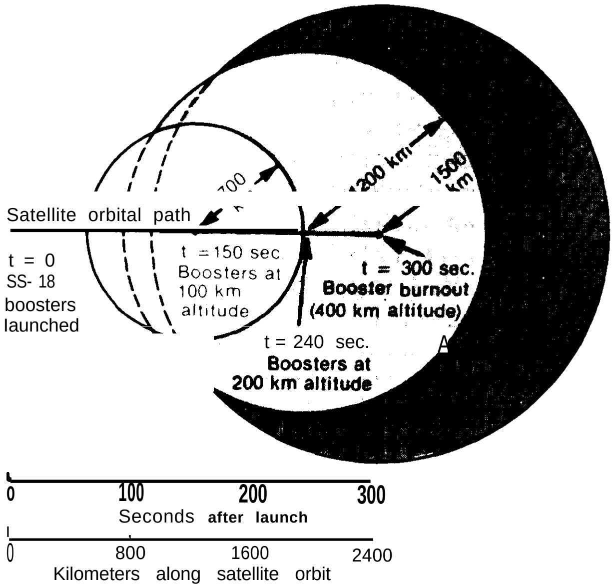
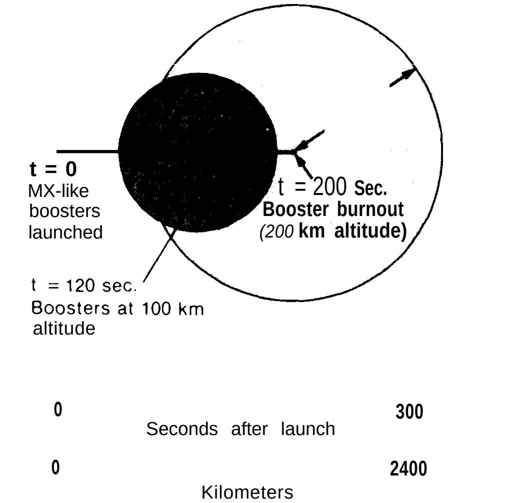


Figure 3.1 l(b)



(b) Same as (a), except the target is the faster-burning MX.

Figure 3.11 View from above (looking down on earth) of coverage by a satellite carrying kinetic energy boost-phase intercept vehicles. The satellite is deployed **in a *400* km orbit. At time t =0, offensive boosters are launched. The satellite can make intercepts by shooting downward or wait until the boosters rise to their burnout altitude and fire nearer to the horizontal. The longer after launch the intercept is made, the farther the rocket intercept vehicles can travel from the satellite to make the intercept. Smaller circles thus correspond to downward firing, larger circles to horizontal firing. The satellite moves from left to right in accordance with its 8 km/see orbital velocity. The area enclosed by all the circles taken together gives the total coverage of the satellite and determines how many satellites are needed in the worldwide constellation for continuous coverage of opposing ICBM fields. All dimensions are to same scale.**

(a) The satellite-based kinetic energy interceptors are capable of 5 km/see velocity relative to the satellite. The attack is on a slow-burning Soviet SS-18.

bility would weigh more like 200 kg). Each carrier satellite must therefore weigh (1 40) x (80) = 11,000 kg. Less than twice this weight can be carried by the space shuttle into the appropriate orbits, so establishing the total 240 satellite constellation requires over 120 shuttle launches in this highly idealized model with idealized rockets and weightless carrier satellites. (A more careful estimation of interceptor design would more than double this load.)

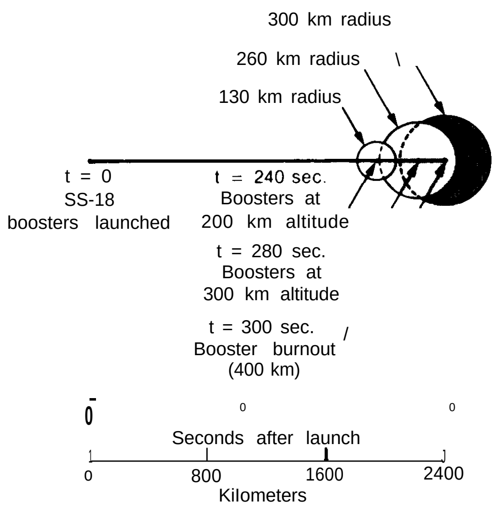
From this baseline, we can consider five excursions:

1. Suppose the velocity capability of the interceptor is doubled to"1 0 km/sec, doubling the effective flyout range to 3 Mm. At this range, 48 satellites complete the constellation, with perhaps as many as eight of them in position to participate in the engagement. Each of the eight satellites must handle 175 Soviet boosters.

   Doubling the velocity capability more than doubles the weight of the rocket required. The reason is simple: to increase the velocity requires more propellant, and the extra propellant must itself be accelerated, requiring yet more propellant. The rocket weight thus grows exponentially with velocity capability. The idealized 10 km/sec rocket weighs ***420*** kg. Each satellite carrying 175 rockets then weighs 75,000 kg and requires some five shuttle launches to orbit. The result is that over 200 shuttle launches are required to orbit the entire (idealized) defense system. Increasing the velocity capability is therefore no escape from large on-orbit weights.

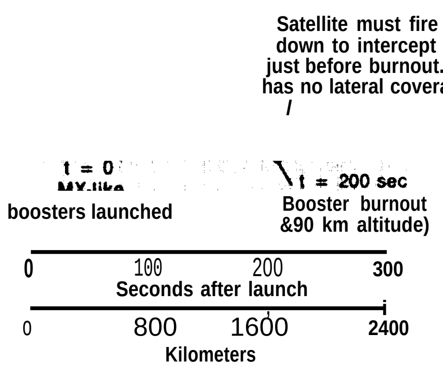
2 The current Soviet ICBM force consists largely of slow-burning liquid-fueled boosters distributed widely over the Soviet Union. Consider the consequences for the U.S. kinetic energy defense system if the Soviets de-

Figure 3.1 l(c)



(c) The High Frontier Global Ballistic Missile Defense (GBMD) concept, with intercept vehicles capable of only 1 km/see velocity relative to the satellite. Intercept of SS-18. In the actual High Frontier proposal, the satellites are in 600 km orbits, giving them even less coverage than shown here.

Figure 3.11(d)



(d) The High Frontier concept has no capability whatsoever for boost-phase intercept of MX.

ploy 100 faster-burning MX-like boosters in one region of the country, so that defensive interceptors have less time to fly to their targets and only one satellite overhead participates in the engagement. MX burns out 200 seconds after launch, so each satellite has an effective range of 1 Mm, requiring a constellation of 400 satellites (fig. 3.11 b).

Each satellite must carry the 100 80-kg rockets needed to handle the attack. An exchange ratio of four 8,000 kg U.S. defensive satellites for every Soviet offensive booster deployed is surely an economic advantage for the U.S.S.R.

3. Soviet deployment of 1,000 Midgetman-like boosters would require a compensating deployment of 400 U.S. satellites, each weighing at least 80,000 kg. A system that forces the United States to such a response is clearly absurd.
4. Soviet fast-burn boosters would be totally immune to the kinetic energy defense system. An interceptor on a satellite in 400 km orbit (lower orbits shorten satellite lifetimes because of atmospheric drag) could not even descend straight down to the fast-burn booster's 100 km burnout altitude in the required 50 seconds, much less have any lateral radius of action.
5. Intercepting SS-18 or MX post-boost vehicles is clearly easier, from the point of view of flyout velocities, than boost-phase intercept. Satellites at 700 km or so altitude would have 500 seconds to fly out to meet the bus when it ascended to their altitude, giving a 2.5 Mm lethal radius.

In conclusion, a rocket-propelled kinetic energy system acting against today's Soviet ICBM arsenal (with no Soviet countermeasures) would require many heavy satellites and would be a dubious investment for the U.S. Soviet deployment of MX-like or Midgetman-like boosters would nullify the United States defense or force the U.S. to large investments in new satellites.

Analysis of the High Frontier Concept

The High Frontier Program[10] proposes a Global Ballistic Missile Defense (GBMD) using rocket propelled interceptors for boost phase intercept. This concept claims to have some utility, at least against the present Soviet ICBM arsenal.

The concept consists of 432 satellites (24 planes of 18 satellites in circular orbits inclined 65 degrees) at an altitude of 600 km. A velocity

[10] Ibid

capability of l km/see relative to the satellite ("truck") is attributed to the interceptor. The interceptors are apparently command guided to the vicinity of the target. The homing sensor is not specified, but short wave infrared homing on the hot rocket plume is implied.

Consider this concept defending against the SS-18 in its boost phase. Since the SS-18 burns out at 400 km altitude 300 seconds after launch, each GBMD satellite has a 0.3 Mm radius of action. Since the satellites are deployed at 600 km altitude, the interceptor must descend 200 km to make an intercept just before burnout, resulting in a lateral radius of action of 0.22 Mm (compare fig. 3.11c, where the satellites are assumed deployed at ***400*** km altitude). With a range this small, thousands of satellites would be needed worldwide for continuous coverage of Soviet ICBM fields. The High Frontier concept with only 432 satellites would therefore have meager coverage of Soviet ICBM fields.

The GBMD concept would have no capability whatsoever against an MX-like booster. Such a booster would burn out before the interceptor could reach it, even if the interceptor were fired straight down (fig. 3.11 d).

It is possible that the High Frontier concept is designed for post-boost intercept rather than boost phase intercept. Its coverage for post-boost intercept, though greater than for boost-phase intercept, would still be only partial. The only example given in the description' of the system is of ***boost phase*** intercept of an SS-18, however. In this example the interceptor is launched 53 seconds ***before*** launch of its target booster, though no explanation is given of how the U.S. defense knows in ***advance*** the precise moment at which the Soviets would launch a given booster. This early launch allows the interceptor to reach its target seconds before burnout. Plume homing, a technique inappropriate for bus intercept, is also implied for the High Frontier concept. Post-boost intercept permits some RVs to be deployed on trajectories carrying them to the United States before intercept; and the entire bus, with its warheads, would continue on to the U.S. after the interceptor collision, with uncertain consequences.

It would therefore appear that the technical characteristics of the High Frontier scheme result in a defensive system of extremely limited capability for boost phase intercept of present Soviet ICBMs and no capability against future MX-like Soviet boosters, even with no Soviet effort to overcome the defense.

' ' I bid, p 103.

3.6 MICROWAVE GENERATORS

Microwaves are short-wavelength radio waves used in radar, satellite communications, and terrestrial communications relays. A number of ideas have been conceived for generating microwaves in space and directing them towards ascending ICBM boosters. The principal technical problem with this type of BMD, generator technology aside, is the uncertain effect the microwaves would have on their target.

The microwaves would propagate through the atmosphere unattenuated at all but the highest power levels. The weapon divergence angle would be very large, producing a spot many km wide at a few hundred km range. From these considerations the following concept emerges: As Soviet ICBMs lift off from their silos, a few microwave generators in space bathe the silo fields with microwaves.

At high power levels, as in a microwave oven, microwaves cause heating in many materials. But in the BMD scheme, the divergence cone is so large that even a prodigious amount of energy emitted from the generator would lead to very small energy deposition per square centimeter on the target (millions of times less than lasers). The microwave pulse received at the booster would resemble the high frequency component of the electromagnetic pulse (EMP) from a high-altitude nuclear detonation. However, even weak microwaves can upset sensitive circuitry if they can reach it.

A metal skin on the booster **would stop the microwave pulse altogether from reaching internal electronics.** The microwave defense must therefore hope that some aperture or conduit is available into the booster, whether by design (as in an antenna), inadvertence, or poor maintenance. If so, and if the electronic circuitry is not or cannot be made resistant to disruption or burnout, the part of the booster's performance dependent on those electronics (perhaps accurate guidance) would be affected.

Because of the very uncertain lethality of microwaves, deployment of space-based generators (if they can ever be built) would be a harassing tactic rather than a confident-kill ballistic missile defense.

3.7 OTHER CONCEPTS

Other directed energy concepts suitable in theory for ballistic missile defense have been broached from time to time. Some of them are listed below. **It is** quite possible that in a few years time a revisit to this subject will find a new panoply of concepts enjoying the front rank of discussion.

1. **Short-wavelength chemical lasers would combine the simplicity and efficiency of the** HF chemical laser with the small mirrors of the short-wavelength excimer and free-electron lasers. Though some ideas have been advanced along these lines, no laser exists which can be said to be a candidate to fulfill this theoretical promise.
2. **Explosive-pumped lasers and particle beams** are said to be under study in the Soviet Union.[12] Such devices might possibly be quite compact, each bomb generating a single huge pulse for impulse kill of a booster. All these schemes are at a very early conceptual stage.
3. **Antimatter beams would penetrate into a** target just like ordinary particle beams, except that when the antiparticle reached the end of its range it would annihilate a particle in the target, freeing a large extra amount of harmful energy. Acceleration of antimatter beams is accomplished exactly as with particle beams, and laboratory beams of antimatter have been used routinely in pure research. One important difference is that antimatter is not freely available in the universe as is matter; the antimatter for the accelerator would have to be produced by the defense system, a formidable and complex undertaking. It is not clear that the extra energy released in the target by an antimatter beam would justify the trouble of producing the beam.

[12] *Aviation Week and Space Technology,* July 28, 1980, p. 47.