

# Report to The American Physical Society of the study group on science and technology of directed energy weapons

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## EXECUTIVE SUMMARY AND MAJOR CONCLUSIONS

The American Physical Society (APS) convened this Study Group to evaluate the status of the science and technology of directed energy weapons (DEWs). The evaluation focuses on a variety of lasers and energetic particle beam technologies for their potential applications to the defense against a ballistic missile attack. This action by the APS was motivated by the divergence of views within the scientific community in the wake of President Reagan's speech on March 23, 1983 in which he called on the U.S. scientific community to develop a system that "...could intercept and destroy strategic ballistic missiles before they reach our soil... ." Directed energy weapons were expected to play a crucial role in the ballistic missile defense (BMD).

The APS charged the Study Group to produce an unclassified report, which would provide the membership of the Society, other scientists and engineers, as well as a wider interested audience, with basic technological information about DEWs. It is hoped that this report, detailing the current state of the art and the future potential of DEWs for strategic defense purposes, will serve as a technical reference point for better-informed public discussions on issues relating to the Strategic Defense Initiative.

The study concentrated on the physical basis of high intensity lasers and energetic particle beams as well as beam control and propagation. Further, the issues of target acquisition, discrimination, beam-material interactions, lethality, power sources, and survivability were studied.

The technology of kinetic energy weapons (KEWs) is not explicitly reviewed, but the role of space-based KEWs in support of DEW systems is considered in the report where appropriate. Further, many important issues concerning command, control, communication, and intelligence (C<sup>3</sup>I), computing hardware, software creation and reliability for battle management, and overall system complexity have been identified but not discussed in detail. Other issues, which were recognized but not addressed, include manpower requirements, costs and cost-effectiveness, arms control and strategic stability, and international and domestic policy implications.

DEW technology is considered in BMD applications both for mid-course discrimination between decoys and reentry vehicles, and for kill in the boost phase, post-boost phase, and mid-course phase of ICBMs. Such consideration has become serious because of numerous technological advances during the past decade in DEW technologies. Although the achievement of an effective defense of the entire nation may require a substantial boost phase intercept component, other strategic defense scenarios, including discrimination for hard point defense

purposes, would place less demanding requirements on DEW systems. The Study Group deemed it important to describe the current state of the art in DEW technology, and to evaluate it with respect to substantial boost phase intercept and mid-course discrimination roles.

**Although substantial progress has been made in many technologies of DEWs over the last two decades, the Study Group finds significant gaps in the scientific and engineering understanding of many issues associated with the development of these technologies. Successful resolution of these issues is critical for the extrapolation to performance levels that would be required in an effective ballistic missile defense system. At present, there is insufficient information to decide whether the required extrapolations can or cannot be achieved. Most crucial elements required for a DEW system need improvements of several orders of magnitude. Because the elements are inter-related, the improvements must be achieved in a mutually consistent manner. We estimate that even in the best of circumstances, a decade or more of intensive research would be required to provide the technical knowledge needed for an informed decision about the potential effectiveness and survivability of directed energy weapon systems. In addition, the important issues of overall system integration and effectiveness depend critically upon information that, to our knowledge, does not yet exist.**

The following observations elaborate on the above finding.

We estimate that all existing candidates for directed energy weapons (DEWs) require one or more orders of magnitude (powers of 10) improvements in power output and beam quality before they may be seriously considered for application in ballistic missile defense systems. In addition, many supporting technologies such as space power, beam control and delivery, sensing, tracking, and discrimination need similar improvements over current performance levels before DEWs could be considered for use against ballistic missiles.

Directed energy weapon candidates are currently in varied states of development. Among the many possibilities, infrared chemical lasers have been under study for the longest period and several high power laboratory models have been built. However, because of their long wavelengths and other technical features, these lasers are perceived to be less attractive candidates for BMD weapons even though they are closest to the

required performance levels in a relative sense. Free electron lasers and excimer lasers are currently perceived as more attractive candidates for BMD missions; but few high power laboratory models have been operated, and the scaling required to reach relevant power levels is estimated to be greater than that for chemical lasers. Nuclear-explosion-pumped x-ray lasers, although the subject of much public discussion, are currently under study at the research level. In our opinion their BMD potential is uncertain.<sup>1</sup> Charged and neutral particle beam devices build on an existing base of accelerator technology but require considerable extrapolations beyond current performance levels.

Supporting technologies are also in varied states of development. In many areas, research is progressing at a rapid pace; for example, schemes for rapid steering of optical beams, and active systems for tracking to microradian class or better.<sup>2</sup> Other critical technologies, such as the techniques for interactive discrimination, are being conceived and addressed. The same caution described above for DEWs applies here, namely, proposed supporting technologies need to be systematically studied before their performance at parameter levels appropriate to BMD applications can be realistically evaluated.

Like any defensive system an effective DEW defensive system must be able to handle an evolving and unpredictable missile threat. In addition to retrofit and redesign of the missiles themselves, decoys and other effective penetration aids can be developed by the offense over the long times required to develop and deploy ballistic missile defenses. In contrast to the technical problems faced in developing DEWs capable of boost phase kill for defense systems, the options available to the offense, including direct attacks on DEW platforms, may be less difficult and costly to develop and may require fewer orders-of-magnitude performance improvements.

A successful BMD system must survive, but survival of high value space-based assets is problematic. Ground-based assets of DEW systems are also subject to threats. Architectures which address the responsive threat are still in their infancy. As an overall BMD system employing directed energy weapons becomes more complex, the currently unresolved issues of computability, testability, and predictability become increasingly critical.

For directed energy weapons to have an important role as a kill mechanism in a strategic defense system designed to defend the entire nation against a ballistic missile attack the following requirements need to be met.

#### **I. For operations in the boost and post-boost phases:**

- A. Sufficient power/energy from the directed energy weapons to kill the ballistic missile in

<sup>1</sup>"X-ray Lasers for Missile Defense," Defense Science and Engineering, November 1986, pp. 17-19.

<sup>2</sup>U.S. Congress, Office of Technology Assessment, *Ballistic Missile Defense Technologies*, OTA-ISC-254 (U.S. Government Printing Office, Washington, D.C., September 1985).

the boost phase, or to kill the post-boost vehicle during the deployment phase.

- B. Sufficient beam quality, pointing accuracy, and agility (retargetability) to deliver lethal powers or energies to targets within the available engagement time provided by the system.
- C. For lasers, optical systems for transmitting beams from sources to targets.
- D. Accurate detection, location of the booster in its plume, and precision tracking from detection until kill is accomplished.
- E. Reliable kill verification.

#### **II. For operations during the mid-course:**

- A. Reliable means of discrimination between reentry vehicles and decoys unless all objects can be destroyed.
- B. Accurate detection, tracking of a very large number of objects in mid-course flight, and kill verification.
- C. Rapid retargeting and sufficient delivered power/energy from the DEW to destroy the reentry vehicles.

#### **III. For terminal phase:**

We do not expect DEWs to play an important role in the terminal phase of the trajectory of ballistic missiles.

#### **IV. For space-based elements:**

- A. Nuclear reactors or other means to supply adequate electrical power for housekeeping functions.
- B. Adequate burst power for operation of DEWs during engagements.
- C. Space qualified reliability of all components and subsystems on the platform notwithstanding long periods of dormancy.

#### **V. For system survivability:**

- A. DEW must be able to operate in a hostile environment during a conflict.
- B. DEW must be integrated in an overall system that includes a survivable command, control, communication, and intelligence (C<sup>3</sup>I) system.

We have examined most of these issues in some detail, except for items III, IV.C and V.B. The following major conclusions are based on detailed considerations in the main body of the report indicated by relevant section numbers in parentheses.

1. We estimate that chemical laser output powers at acceptable beam quality need to be increased by at least one order of magnitude for HF/DF lasers for use as an effective kill weapon in the boost phase. Similarly for atomic iodine lasers, at least five orders of magnitude improvement is necessary.

The HF/DF cw chemical lasers have been stated to yield power levels exceeding 1 MW with acceptable beam quality.<sup>3</sup> Based on these data, we estimate that even the least demanding strategic defense applications require power levels to be increased further by at least a factor of twenty while retaining beam quality. However, the laser geometry which achieved the above demonstration will have scaling problems to higher power levels; thus, the combination of power scaling and adequate beam quality must be explored for some different chemical laser design, yet to be demonstrated. A chemically pumped atomic iodine laser at  $1.3\ \mu\text{m}$  has been developed, although at this point only 5 kW of continuous wave power has been demonstrated. Because of atmospheric absorption, the HF laser ( $\lambda = 2.8\ \mu\text{m}$ ) would have to be deployed on space platforms, while the DF laser ( $\lambda = 3.8\ \mu\text{m}$ ) and the atomic iodine laser ( $\lambda = 1.3\ \mu\text{m}$ ) could also operate on the ground. When based in space, chemical lasers face a special set of problems arising from vibrations and the exhaust of the burnt fuel (Section 3.2).

2. **We estimate that the pulse energy from excimer lasers for strategic defense applications needs improvement by at least four orders of magnitude over that currently achieved. Many advances are needed to achieve the required repetitive pulsing of these lasers at full scale.**

The pulsed excimer lasers have demonstrated single pulse energies of about 10 kJ in  $1\ \mu\text{s}$  pulses from a single module<sup>4</sup> (Section 3.3). This laser currently uses krypton fluoride ( $\lambda = 249\ \text{nm}$ ); the other principal contender excimer species is xenon chloride ( $\lambda = 308\ \text{nm}$ ). From our estimates, assuming an overall propagation loss factor of four (relay mirror losses, Rayleigh scattering losses, and atmospheric losses), ground-based excimer lasers for strategic defense applications must produce at least 100 MJ of energy in a single pulse or pulse train with a total duration between several and several hundred microseconds (Section 6.3). To kill multiple targets a firing rate of ten per second would be desirable. For thermal kill 1 GW of average power would be required (Section 6.2). The gap of four orders of magnitude might be bridged by first combining lasers into modules at the hundreds of kilowatt level, then combining many modules optically. To produce high optical quality beams from the modules, the output from low optical quality amplifier apertures may be combined using stimulated Raman scattering or other means (Section 3.3). We estimate that the techniques for Raman beam combination must be scaled up by two orders of magnitude or more in combined laser power and efficiency from that which has been demonstrated in the laboratory. The technology for phase locking a large number of modules is not yet demonstrated (Section 5.4).

<sup>3</sup>See Reference 19 of Chapter 3.

<sup>4</sup>See Reference 39 of Chapter 3.

3. **Free electron lasers suitable for strategic defense applications, operating near  $1\ \mu\text{m}$ , require validation of several physical concepts.**

The free electron laser (FEL) is one of the newest laser technologies to be demonstrated. Peak powers of approximately 1 MW have been produced at a wavelength of  $1\ \mu\text{m}$ ; peak powers of approximately 1 GW have been produced at a wavelength of 8 mm, demonstrating high gain and high efficiency at that wavelength.<sup>5</sup> Scaling to short wavelengths at high powers is a more difficult technical problem than simply increasing average power. Obtaining high efficiency, high power free electron laser operation at  $1\ \mu\text{m}$  requires experimental verification of physical concepts which thus far are only theoretically developed, e.g., optical guiding and transverse sextupole focusing for the amplifier configuration, and sideband and harmonic control for the oscillator configuration.<sup>6</sup> We estimate that for strategic defense applications, a ground-based free electron laser should produce an average power level of at least 1 GW at  $1\ \mu\text{m}$  wavelength, corresponding to peak powers of 0.1–1.0 TW (Sections 3.4 and 6.3).

4. **Nuclear-explosion-pumped x-ray lasers require validation of many of the physical concepts before their application to strategic defense can be evaluated.<sup>7</sup>**

A subcommittee of the Study Group reviewed the progress in x-ray lasers. A nuclear-explosion-pumped x-ray laser has been demonstrated. This is a research program where numerous physics and engineering issues are still being examined. What has not been proven is whether it will be possible to make a militarily useful x-ray laser<sup>7</sup> (Section 3.5). Atmospheric interaction limits the use of nuclear-explosion-pumped x-ray lasers to altitudes greater than about 80 km (Section 5.10). The high energy-to-weight ratio of the nuclear explosives makes it possible for these devices to be considered for "pop-up" deployment (Section 9.3).

5. **We estimate that neutral particle beam (NPB) accelerators operating at the necessary beam current levels ( $\geq 100\ \text{mA}$ ) must be scaled up by two orders of magnitude in voltage and duty cycle with no increase in normalized beam emittance. The required pointing accuracy and retargeting rates remain to be achieved. These devices must be based in space to avoid beam loss via atmospheric interactions.**

<sup>5</sup>T. J. Orzechowski *et al.*, Phys. Rev. Lett. **57**, 2172–2174 (1986).

<sup>6</sup>See Reference 74 in Chapter 3.

<sup>7</sup>E. Walbridge, "Angle Constraint for Nuclear Pumped X-ray Laser Weapons," Nature **310**, 180–182 (1984), and references cited therein; George Miller (Associate Director, Lawrence Livermore National Laboratory) quoted in "Experts Cast Doubt on X-ray Lasers," Science **230**, 647 (1985).

Structural kills with NPB devices require an equivalent charge of about 1 Coulomb (e.g., 100 mA for 10 s) delivered at a few hundred MeV, with a beam divergence of 0.75–1.5  $\mu$ rad (as discussed and calculated in Sections 4.3 and 6.4). Disruption of electronic function because of radiation dose could occur at significantly lower beam parameters, although this kill mechanism is system dependent, and kill assessment may be difficult (Chapter 4).

Existing radio frequency (rf) ion accelerators have achieved particle kinetic energies of several hundred MeV, but at beam current levels two orders of magnitude below the required levels (Section 4.3). New negative ion sources have achieved the necessary peak currents and low beam emittances, but such sources have not been reported to operate continuously. Additional issues are emittance growth of the high current beams in the first part of the accelerator, and the development of large bore magnetic optics. Power requirements and weight are also significant issues (Chapter 8).

Ionization of the neutral beam atoms via atmospheric collision (and subsequent ion deflection in earth's magnetic field) establishes a minimum operating altitude of about 120 km for beam kinetic energies of a few hundred MeV (Section 4.1).

NPB devices have been suggested for use in an interactive mid-course discrimination mode (identifying massive reentry vehicles in a postulated threat cloud which includes light weight decoys). In this case the beam power requirements will not change significantly, but the target dwell times may be reduced by a factor of 10–1000 compared to boost phase kill requirements, and retargeting rates of  $> 10 \text{ s}^{-1}$  may be necessary. Hence, device issues which will require new ideas and further exploration for this mission are development of rapid retargeting mechanisms using magnetic beam steering and fast accurate methods for beam direction sensing (Section 7.7).

6. **Energetic electron beams require propagation in laser-created plasma channels in order to avoid beam deflection in the earth's magnetic field; this restricts the operational altitude at the low end by beam instability and at the high end by ion density starvation. We estimate that booster kill applications require a scale-up in accelerator voltage by at least one order of magnitude, in pulse duration by at least two orders of magnitude, and in average powers by at least three orders of magnitude. Active discrimination applications require scale-up in pulse duration by at least two orders of magnitude, and in average power by at least two orders of magnitude. The lasers needed for the creation of plasma channels require**

**development. We estimate that propagation distances must be increased by several orders of magnitude.**

Propagation through a laser-created plasma channel is necessary to prevent beam space-charge blow-up and beam bending in the earth's magnetic field. This implies both a lower and an upper altitude operational limitations. The lower bound arises from beam stability considerations, while the upper bound results from ion density starvation. This mechanism for beam guiding has been successfully demonstrated in the laboratory, but over distances of only 95 m<sup>8</sup> (Section 4.2). For optimum beam currents of a few kiloamperes, delivering lethal pulses to distances in excess of 1000 km will require beam kinetic energies of several hundred MeV. Useful ranges for some suggested interactive discrimination applications could be as small as a few hundred kilometers, in which case the particle energy requirement would decrease by an order of magnitude (Section 7.7). Existing linear induction accelerators have demonstrated the necessary peak power capability (tens of MeV at peak currents of tens of kiloamperes and pulse repetition rates of a few hertz), although not for required pulse lengths of microseconds (Section 4.2). Although several approaches have been suggested, the laser technologies required for creating the plasma channel have not been demonstrated. Because of the limited engagement space, rapid retargeting ( $\sim 0.1 \text{ sec}$ ) and high repetition rates ( $> 10 \text{ Hz}$ ) are essential.

7. **Phase correction techniques are required for obtaining near diffraction limited performance of most types of laser weapon devices. Further, phase control techniques are required for coherently combining outputs from different modules in a multiple laser system into a single diffraction limited beam. These techniques, demonstrated at low powers, must be scaled up by many orders of magnitude in power.**

High power laser systems are likely to require active control and correction of the optical phase of the output beam to reach the nearly diffraction limited performance desired for strategic defense applications. Several techniques are available for these purposes. These include correction of slowly varying phase errors with low spatial frequencies through use of adaptive optics and self-correction of phase errors using nonlinear phase conjugation techniques, such as stimulated Brillouin scattering, or four-wave mixing; and combining beams from multiple apertures by phase locking of multiple laser modules, or through stimulated Raman scattering. Each of the laser technologies under development may use different types of phase corrections. All of these approaches for phase correction have been demonstrated

<sup>8</sup>G. J. Caporaso, F. Rainer, W. E. Martin, D. S. Prono, and A. G. Cole, "Laser Guiding of Electron Beams in Advanced Test Acceleration," Phys. Rev. Lett. **57**, 1591–1594, (1986).

on a laboratory scale, but extensions to high power systems and large apertures remain to be demonstrated (Section 5.4).

8. **Dynamic phasing of arrays of telescopes requires extensive development in order to obtain large effective aperture optical systems. As calculations indicate (Section 5.4.5), the number of phase correcting elements must be increased by at least two orders of magnitude over currently demonstrated values.**

Optical laser systems will require large effective optical apertures in order to achieve the necessary beam intensity on target. Such radiating apertures have to provide near diffraction limited beams which can be rapidly retargeted. The state of the art for ground-based monolithic telescope primaries for astronomical applications is about 8 m.<sup>9</sup> Torque requirements for rapid steering of large telescopes limit monolithic telescopes to approximately 8 m aperture; the larger "effective aperture" primaries have to be synthesized by dynamically phasing a number of smaller telescopes. Such phasing of a number of telescopes has been accomplished<sup>10</sup> by dynamically controlling the wavefront "piston," tilt, and focus of the laser beams feeding each telescope of the array. This adds complexity to the system but allows beam pointing in terms of target tracking without requiring slewing of telescopes (Section 5.2).

The phase front of the outgoing wave is monitored in such phasing schemes, and corrections are applied via electrically driven actuators. Components for control of about several hundred such actuators are commercially available. For the large apertures contemplated for BMD applications the number of actuators needed lies between ten thousand and one hundred thousand, a substantial extrapolation. The technology of phase-controlling an array of primary mirrors is in an early stage of development. Scaling of such arrays to high power has not been accomplished (Section 5.4).

An alternative approach is to use telescopes where the primaries are made out of single large flexible membranes which are appropriately distorted by many actuators. The concept has been demonstrated only for small flexible primaries at low powers. Extensions to larger mirrors at higher powers remains to be shown (Section 5.4).

9. **The optical coatings of large primary mirrors are particularly vulnerable in space-based optical systems.**

The large primary mirror, which directs the laser beam towards the target, is particularly vulnerable to radiation from other lasers (from any direction) (Section 5.6). Based on discussions with commercial vendors, we find that the cw power loading threshold for reflective coatings

is about  $100 \text{ kW cm}^{-2}$ . For laser pulses of a few microseconds or less, the damage threshold will be about  $8 \text{ J cm}^{-2}$  of absorbed energies, corresponding to peak powers of  $10 \text{ MW cm}^{-2}$ . These damage thresholds are for operation at a nominal laser wavelength of  $3 \mu\text{m}$  (Section 6.2). If attacked by lasers at other wavelengths in the visible, near ultraviolet (UV), or x-ray region, the damage threshold may be significantly lower. Further, there is a possibility of damage to the high reflectivity coatings from energetic particles in the ambient background, i.e., MeV protons and electrons, during long term residence of the high reflectivity mirrors in space.

10. **Small secondary mirrors in the optical trains of high power lasers will need very low absorptivity coatings and will have to be cooled.**

The requisite power levels for ballistic missile defense lethality will necessitate cooling of the small mirrors in the optical train of high power lasers to prevent damage. A beam power of 1 GW on a mirror of  $100 \text{ cm}^2$  area implies an incident power of  $10^7 \text{ W cm}^{-2}$ . High reflectivity coatings with less than  $10^{-4}$  absorptivity are needed. Such mirrors have been demonstrated, and lead to an absorbed power of  $1 \text{ kW cm}^{-2}$ . Cooled silicon or silicon carbide mirrors show promise for raising this threshold (Section 5.5).

11. **Ground-based laser systems for BMD applications need geographical multiplicity to deal with adverse weather conditions.**

For each ground-based laser system which must be available in battle, a number of geographically separated laser sites are needed to provide availability of at least one site in the system when the others are obscured by adverse climatic conditions. These locations must be separated by distances greater than the coherence length scale for weather patterns. Based on weather statistics, a multiplicity of five independent ground-based lasers could provide a 99.7% availability. By going to seven climatically isolated locations in the continental U.S., availability of 99.97% is possible. At each of these sites, local cloud cover conditions require further multiplicity of the large ground telescopes, separated by few km (Section 5.4).

12. **Ground-based laser systems require techniques for correcting atmospheric propagation aberrations. We estimate that these techniques must be extended by at least two orders of magnitude in resolution (number of actuators) than presently demonstrated. Phase correction techniques must be demonstrated at high powers.**

Ground-based laser systems will require either linear or nonlinear adaptive optics of a very sophisticated nature in order to precompensate the laser beam for

<sup>9</sup>C. H. Townes (private communication).

<sup>10</sup>See References 2 and 3 of Chapter 5.

atmospheric aberrations caused by atmospheric turbulence and by thermal blooming induced by the laser beam itself. A retroreflector or a low power laser located at an appropriate point-ahead position in front of a space-based relay mirror would provide a reference source for transmission through the atmosphere to the ground telescope, where the wavefront would be analyzed for acquired aberrations due to the atmosphere. This information would be used to control adaptive optics of high resolution ( $\geq 10\,000$  actuators per aperture) at high bandwidths ( $\approx 1.0$  kHz). This technique requires an extensive computational capability. Such atmospheric compensation experiments have been successfully demonstrated at low powers (no thermal blooming in the atmosphere) and at average atmospheric viewing conditions for Mt. Haleakala, Maui (moderate turbulence) with a small number of actuators ( $< 100$ ). At high power levels, the turbulence may be high enough to cause a beam intensity redistribution which could be uncorrectable (Sections 5.2 and 5.4).

The incorporation of phase correction schemes in pulsed induction linac FEL amplifier is particularly stressing because the atmospheric compensation must be carried at high power levels. Atmospheric compensation techniques are needed for point-ahead angles which are large and for targets which may be noncooperative.

**13. Uplink in a ground-based laser system faces transmission losses in the atmosphere.**

The uplink of high power output from a ground-based laser system faces natural atmospheric losses such as Rayleigh scattering, which stress the short wavelength systems, and atmospheric absorption losses, primarily from water vapor, which stress the longer wavelength systems. The optimum wavelength region is  $0.4\text{--}1.0\ \mu\text{m}$ . Even in this region, nonlinear effects such as stimulated Raman scattering and thermal blooming force the use of large final transmitting optics on ground (Section 5.4).

**14. Nonlinear scattering processes in the atmosphere impose a lower limit on the altitude at which targets can be attacked with a laser beam from space.**

Power delivery downward through the atmosphere to rising targets may be limited by stimulated Raman scattering and thermal blooming by ozone absorption. These phenomena limit the minimum attack altitude to 80 km for very short pulses, or require a longer pulselength (1–10 ms), because the laser beam must be focused to a small,  $\sim 1\ \text{m}^2$ , spot size on the target. At the required high laser intensities, nonlinear effects may throw the optical power out of the focused beam before reaching the target (Section 5.4).

**15. Detection and acquisition of ICBM launches will pose stringent requirements for high detection probability and low false alarm rates.**

The achievement of boost phase kill probabilities of 90% implies booster detection and acquisition probabilities of better than 90%. In addition, successful operation of a mid-course system depends importantly on being given good booster trajectory information. Of even greater importance, low false alarm rates are required so that a BMD system is not activated in peace time because of the false alarms (Section 7.2).

**16. For boost phase, infrared tracking of missile plumes will have to be supplemented by other means to support sub-microradian aiming requirements of DEWs.**

Tracking of missiles by detecting the intense short wavelength infrared (SWIR) radiation from booster plumes is a technology which has been pursued for some time. The plume brightness greatly exceeds that of the missile, and the position of the missile within the plume depends in a complex manner on altitude, missile type, rocket motor, fuel characteristics, etc., and is susceptible to variation by the offense in a manner which cannot be predicted by the defense. Other passive means of accurately locating and tracking missiles in boost phase are in early stages of study (Section 7.5).

Active means of tracking may be required. Of the likely candidates, microwave radars are the most developed although electronic countermeasures for them are also well developed. Optical radars may be more promising, if the illuminating beam can be rapidly retargeted, and if an imaging capability can be achieved (either range-Doppler or angle-angle systems would be sufficient). If rapid retargeting cannot be developed and if power-aperture requirements for microwave radars become too severe hundreds to thousands of space platforms will be needed (Section 7.6).

**17. For post-boost and mid-course, precision tracking will require active sensor systems.**

Observation of PBVs and RVs (at 300 K) will require detection of weak thermal signatures since these signatures vary as  $T^4$ . Similar signatures are associated with objects in mid-course. Thermal detectors in the long wavelength infrared (LWIR) can be used only above the earth's limb against a cold space background. Low noise LWIR detector assemblies having the appropriate resolution, i.e., large element arrays, are being developed. Because of the long wavelengths involved (8–12  $\mu\text{m}$ ), sub-microradian tracking accuracy is not feasible in LWIR without using telescopes with apertures in excess of 10 m (Section 7.2). Thus, thermal detectors will have to be supplemented by some active means such as microwave or optical radars. A large number of space-based platforms will be required. These might be the same platforms that are performing similar duties in the boost phase (Section 7.3).

- 18. For mid-course, when the RVs are interspersed with penetration aids, interactive discrimination may be required. At present the application of DEW technologies to this task is in the conceptual and early experimental stage.**

Missiles which survive the boost phase can deploy large numbers of decoys and other penetration aids. Since LWIR and radar signatures depend largely on surface phenomena, there are many options available to the offense desiring to confuse or saturate the defense (use of balloons, for example). Directed energy technologies may offer the possibility of "mass" discrimination by interactive, perturbing means, e.g., detection of particle-beam-induced secondary emissions or velocity changes caused by laser-ablation-induced impulse. DEW platforms absent from the boost phase intercept theater might be useful in this function. Such interactive discrimination is in a conceptual and early experimental stage, and would require large numbers of additional sensor/detector platforms, plus the ability to function in nuclear-disturbed backgrounds (Section 7.7).

- 19. The development of an effective boost phase defense is highly desirable, perhaps essential for limiting the number of objects with which the mid-course and terminal defense elements must cope.**

Given the present number of Soviet boosters and their capability, the offense can deploy half a million or more threat objects (reentry vehicles and decoys). Boost phase attrition is required if mid-course discrimination systems can deal with only a limited number of threat objects. Even an 80% effective boost phase defense would leave 100 000 or more objects entering the mid-course phase. If further increases in the offensive threat or degraded performance of the boost phase tier overload the tracking and discrimination capabilities of later tiers, then the overall performance of the defensive system would degrade catastrophically rather than linearly when saturation is approached. The tracking and discrimination of tens to hundreds of thousands of objects during the mid-course phase poses formidable challenges to sensors and battle management computers. If discrimination requires birth-to-death tracking of all threat objects, these problems become even more demanding (Section 2.3).

- 20. Housekeeping power requirements for operational maintenance of many space platforms for strategic defense applications necessitate nuclear reactor driven power plants on each of these platforms.**

The power requirements for "housekeeping," i.e., the requirements for a space platform to control attitude, to cool mirrors, to receive and transmit information, to operate radars, etc., is estimated to be in the range of 100 kW–700 kW of continuous power. This would require a

nuclear reactor driven power plant for each platform, necessitating perhaps a hundred or more of these nuclear reactors in space. These foregoing needs require solving many challenging engineering problems not yet explored. Cooling of large space-based power plants is a very difficult task (Chapter 8).

- 21. During engagements prime power requirements for electrically driven space-based DEW present significant technical obstacles.**

The prime power required for electrically driven DEW, e.g., electron accelerator for a space-based free electron laser, is estimated to be 1 GW. For a space-based neutral particle beam weapon, the electrical power requirements range from 100 MW (minimum) to 1 GW depending on the desired range and retargeting rates. This power could be provided by large chemical or nuclear rocket engines and generators, deployed at considerable distances or otherwise decoupled from the DEW platforms in order to avoid mechanical disturbances and effects of exhaust gases. This may require complex power transfer systems comprising cables, microwave systems, etc. Correspondingly, chemical fuel consumption would be more than five tons per minute of operation per platform (Section 8.3).

- 22. Survivability is an essential requirement of any BMD system employing space-based assets; such survivability is highly questionable at present. Evaluation of this issue requires a systems approach that includes hardening, active defense, and operational tactics. During the deployment phase, the space-based assets are especially vulnerable.**

The space platforms carry sensors, optical mirrors, or radar dishes, many of which have considerably lower damage thresholds than do the hardened boosters, post-boost buses, and RVs. While sensors and optical mirrors on satellite platforms may be shielded during long periods of inactivity, they would be exposed when put on alert prior to an impending ICBM attack. Such an attack could be preceded by an attack on these platforms by space-based and ground-based DEW, space-based kinetic energy weapons (KEWs), space mines, or direct ascent nuclear and non-nuclear antisatellite (ASAT) weapons of the offense. Moreover, the system must be developed by a process of accumulation of space assets; during this period of accumulation the system is less capable of defending itself (Sections 9.3 and 9.4).

The ground-based laser systems for strategic defense applications require a substantial number of space-based optical elements and space-based sensors. The space-based optical elements include telescopes with large primary mirrors, the size and numbers of which will depend on the basing modes for the relay and the fighting mirrors. These space-based elements entail the same

vulnerability as any other space-based components (Section 9.3).

- 23. Survivability of ground-based facilities also raises serious issues. The relatively small number of large facilities associated with ground-based laser sites makes these facilities high-value targets.**

The ground-based laser BMD facilities must be successfully protected from direct attack from many threats (e.g., cruise missiles, sabotage, etc.), in addition to ballistic missiles. Thus, any strategic defense system depending on ground-based lasers, or on other ground-based facilities which cannot be extensively proliferated, must be effective in defending against more threats than just ballistic missiles (Section 9.3).

- 24. Directed energy weapons with capabilities below those needed for many ballistic missile defense applications can threaten space-based assets of a defensive system.**

If a DEW falls short of ballistic missile defense requirements, it may still be a credible threat to space-based assets. Space-based platforms move in known orbits and can therefore be targeted over much longer time spans than ballistic missile boosters, post-boost buses, or reentry vehicles. The defense platforms may have key components that are more vulnerable than the boosters and the reentry vehicles. Furthermore, space-based platforms in low earth orbits can be attacked from

shorter ranges than those required for boost phase intercepts (Sections 9.3 and 9.6).

- 25. X-ray lasers driven by nuclear explosions would constitute a special threat to space-based sensors, electronics, and optics.**

The high energy-to-weight ratio of nuclear explosive devices driving the directed energy beam weapons permits their use as "pop-up" devices. For this reason the x-ray laser, if successfully developed, would constitute a particularly serious threat against space-based assets of a BMD (Sections 3.5 and 9.3).

- 26. Since a long time will be required to develop and deploy an effective ballistic missile defense, it follows that a considerable time will be available for responses by the offense. Any defense will have to be designed to handle a variety of responses since a specific threat cannot be predicted accurately in advance of deployment.**

A thorough understanding of practical responses, such as attacks on the defensive assets, hardening of offensive systems, and rapid deployment of large number of decoys, must be established before conclusions about the technical feasibility and cost-effectiveness of a defensive system can be made. A DEW system designed for today's threat is likely to be inadequate for the threat that it will face when deployed (Section 2.3 and Chapter 9).



## Chapter 1

### OVERVIEW

#### CONTENTS

- 1.1 Background
- 1.2 Charter of the Study
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- 1.4 Perspective
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#### 1.1 BACKGROUND

On March 23, 1983, President Reagan called upon the nation and its technological community to make a major intellectual and physical effort to find an alternative to the current policy of assuring national security through the threat of retaliation to deter a ballistic missile attack. After that speech the President ordered studies to explore further the promise of ballistic missile defense (BMD), and in 1984 the Department of Defense established an organization to expand and accelerate research in ballistic missile defense technologies. This program is now called the "Strategic Defense Initiative" (SDI).

The study of defense against ballistic missiles is not new; vigorous research efforts to develop antiballistic missile (ABM) technologies were begun in the late 1950s. However, by the late 1960s it had become evident that ABM defenses would not be sufficiently effective to protect cities or other large, vulnerable targets, and the emphasis shifted to defense of hard military targets, such as ICBM silos. By 1972 it became apparent that the existing technology could not satisfy this mission objective either. In this case the critical weakness of the system lay not in the performance of the interceptor rockets or the nuclear weapons they carried. Rather, it lay in the acquisition, tracking, discrimination, and battle management functions, and especially in their vulnerability to direct attack.

During the next 10 years there were significant advances in several potentially relevant ABM technologies. For example, computers became smaller, cheaper, and more capable; higher frequency, higher power radars became available and overall radar systems became more compact, durable, and cheaper; and various directed energy technologies (lasers and particle beams) experienced rapid development. A virtually continuous series of government-sponsored studies of advanced

strategic defense technologies were performed by organizations such as the Defense Science Board, the White House Science Council, and various private contractors during the period of 1979–83.

Following the President's speech the Department of Defense was instructed to reexamine the state of knowledge and policy relevant to the BMD problem. Three separate studies were commissioned and these worked through the summer and early autumn of 1983. Two of these dealt with policy issues; the third, the Defense Technologies Study Team (DTST, popularly known as the Fletcher Panel), reexamined the readiness and potential of technologies to deal with interception of ICBMs in all phases of their trajectories. Based on the results of separate study subgroups dealing with the major technical aspects of the BMD problem — directed energy weapons (DEWs), kinetic energy weapons (KEWs), surveillance, acquisition, tracking and kill assessment, and battle management and system integration — the Fletcher Panel reported that it found many possibilities for dealing with these aspects. It further concluded that since none of the problems could be solved with existing technology, major development would be needed over an extended period of time. The recommendations of the Fletcher Panel resulted in the creation of the Strategic Defense Initiative Organization, which consolidated virtually all the BMD-relevant research in the government.

The ensuing intense debate unleashed by the Strategic Defense Initiative has largely focused on philosophical and political considerations, while technological options and limitations have not been analyzed in sufficient detail, or details may only be found in classified documents.<sup>1</sup> Some technical issues are discussed in reports by the Office of Technology Assessment,<sup>2</sup> by the Union of Concerned Scientists,<sup>3</sup> by the Center for International Security and Arms Control of Stanford University,<sup>4</sup> by the American Academy of Arts and Sciences,<sup>5</sup> by the Brookings Institution,<sup>6</sup> and other articles in professional journals,<sup>7–9</sup> and others.<sup>10</sup> In many reports the main thrust deals with implications for domestic and foreign policy. These reports are generally addressed to a broad audience and the scientific and technological analyses are necessarily abridged. The cited reports cover a broad range of complex questions raised by the SDI program, including its impact on arms control negotiations as well as existing international treaties, on stabilizing and destabilizing factors in the current offensive balance, on economic impact, and broad systems considerations.

## 1.2 CHARTER OF THE STUDY

The American Physical Society recognized that there were considerable uncertainties and differences of opinion among its members concerning the present state of the art of directed energy technologies, as well as the requirements for satisfying various ballistic missile defense missions (boost phase defense, mid-course discrimination, etc.). It, therefore, commissioned a study of the science and technology of directed energy weapons through its Council action on November 20, 1983. By November 1984, a Study Group comprising scientists and engineers from federal laboratories, industrial organizations, and universities had been constituted. Some members of the Group were (and are) actively involved in directed energy research. The Group was specifically chartered to examine the status of, and requirements for, directed energy weapon technologies, and to document its findings in an unclassified report.

Responding to its charter, the Group has focused on the following central theme: perform an in-depth review of the several directed energy weapon technologies and estimate the parameter requirements necessary for accomplishing various future BMD missions. In light of this focus, we do not discuss KEW technologies nor do we address the complex issues associated with battle management and C<sup>3</sup>I (command, communications, control, and intelligence) including testability and reliability of the software. Also, this report does not address the related issues of arms control and strategic stability. Each of these issues is, however, sufficiently important to merit a separate study.

This study specifically does not evaluate the current SDI program, but rather establishes a framework which may be helpful to others interested in the evaluation of the DEW component of this program. The Group hopes that the report which follows will serve as a useful technical reference for members of the APS, and for other scientists and engineers, as well as for a wider audience in order that discussions of the issues related to the Strategic Defense Initiative be better informed.

## 1.3 SCOPE OF THE STUDY

Following this brief overview, the report first describes the targets at which the DEWs would be aimed. Thus, Chapter 2 deals with both the current and responsive missile threat. Next, all major candidates for laser DEWs are discussed in Chapter 3. Detailed technical information is presented for chemical lasers, excimer lasers, and free electron lasers, while only the principles of x-ray lasers are described because of classification restrictions. The state of the art of each and the requirements for DEW devices intended for BMD applications are given. The other category of DEW devices, the relativistic particle beams, is described in Chapter 4 along with their propagation characteristics.

Characteristics of photon beam propagation are described in Chapter 5 which includes the technology of beam control, delivery, and atmospheric beam propagation effects.

The basic physical mechanisms by which photon beams and relativistic particle beams can damage targets are described in Chapter 6. The requirement of lethality, that the target be either destroyed or made inoperative, demands that a sufficient amount of energy and/or power must be delivered to the target.

The beams from DEWs must be directed at the targets, i.e., they must intercept hostile ballistic missiles and/or their payloads. Acquisition, tracking, and discrimination of objects require sensor platforms, radars, and possibly laser and particle beam tracking and discriminating devices in space. These problems are discussed in Chapter 7. The power requirements for space-based platforms present special problems which are examined in Chapter 8.

The important issue of survivability of DEWs is discussed in Chapter 9. It depends sensitively on both device parameters and system architecture. The overall architecture of a defensive system depends heavily on considerations of many factors. These include command, control, communication, and intelligence (C<sup>3</sup>I), hardware and software development and reliability for battle management, the possible inclusion of kinetic energy weapons, etc. The integration of all these components and systems into an overall system presents extremely challenging problems, some of which are enumerated in Appendix A. A discussion of satellite constellations is presented in Appendix B.

The combination of lethality, propagation, and range requirements determines the brightness required for directed energy weapons. For defense of the entire nation, including protection of population centers, via boost phase kill, the brightness requirements exceed by orders of magnitude the present state of the art of various types of lasers, particle beam devices, optical delivery systems, acquisition platforms, power supplies, etc. This is the main thrust of the detailed conclusions of this study which are presented in the Executive Summary.

## 1.4 PERSPECTIVE

The Group notes that predicting the course of technological progress can be particularly difficult. Very optimistic predictions are often made for technologies or schemes which are at very early stages of development. Whenever orders of magnitude of improvement are necessary in operating parameters, it is likely that many new discoveries and inventions will have to be made. The discrepancy between the present state of the art of DEWs and the ultimate requirements is so large that major gaps in technical understanding must be closed before engineering technology verification could be productive.

Forcing immature technology to this verification phase can have two undesirable consequences. First, it tends to freeze technology at levels inadequate for its ultimate goals. And second, it tends to absorb resources which could otherwise be used for research on more promising ideas.

Past experience with the progression from theoretical concept, via proof of principle, understanding of details, technical development, engineering, to eventual deployment in a very large system, shows that technology typically is frozen several years before deployment, and basic science more than a decade before that.<sup>11</sup> Because of the extensive development needed in many technological areas important to the systems, we judge that the deployment of a substantial DEW component in a BMD system cannot be foreseen before the year 2000.

The offense can use the long development test and deployment time to respond with similar, or dissimilar, technological developments. The Group did not review classified intelligence information about the likely technological responses from the Soviet Union, but rather relied primarily on general scientific and engineering principles in considering potential countermeasures. The uncertainty about the responsive threat, in turn, may raise the requirements for lethality and will make survivability more uncertain. A deployed DEW defensive system may have to face the threat of DEWs on the offensive side, in addition to other conventional threats. If a DEW system is capable of disabling a ballistic missile in the boost or post-boost phase, it is likely that it also meets the lethality requirements for damaging a space platform.

Because achieving the ultimate goal of population defense appears so difficult from a technological point of view, many people have advocated more limited missions for DEWs, including antisatellite (ASAT) weapons, and target discrimination. DEW requirements can be considerably lower for these reduced objectives. The role of DEWs could be minor, if not negligible, in the case only hard-point defense of land-based silos is contemplated.

## 1.5 LIMITATIONS IN SCOPE

The sheer size of the technological development of DEWs, let alone deployment, is such that it raises questions about manpower and economic cost. Engineering manpower requirements are likely to be high. The Group believes that these are very important issues, and should be studied because of their possible impact on the civilian economy, international competitiveness, the armed services, and technical manpower. The Group notes the existence of these issues but does not address them and it refrains from conclusions about them.

Another important issue which has not been dealt with in detail is launch costs. Deployment of any BMD system with extensive space-based components will require that the cost of placing mass in orbit be significantly reduced. We have not evaluated the prospects for success in this endeavor. However, it is

worth noting that such major cost reductions would also produce major changes in the nature and capabilities of the offensive threat.

Finally, this study does not deal with the very important issue of cost effectiveness of directed energy weapons in their use in ballistic missile defense. Cost effectiveness is variously defined, but the most cogent definition is contained in one of the Nitze criteria<sup>12</sup> which requires the incremental cost of providing a ballistic missile defense to be less than the incremental cost incurred by the enemy for overcoming the defensive actions. For example, a recent paper by Field and Spergel<sup>13</sup> has outlined a methodology for one aspect of DEW which may be used for such semiquantitative but exceedingly important evaluations of specific technologies. Cost estimates for the whole system are necessary, but are likely to be much more complex. Blechman and Utgoff<sup>14</sup> have described a heuristic approach to economic implications of strategic defense. Other limitations in scope have already been mentioned in Sections 1.2 and 1.3.

## 1.6 ACKNOWLEDGMENTS

Financial support was received from Carnegie Corporation of New York and the MacArthur Foundation. The study also received full cooperation from the Strategic Defense Initiative Organization and from the Office of Science and Technology Policy. We are grateful to all officials and individuals who helped us with extensive briefings. We also wish to thank Dr. R. Cunningham, Dr. P. L. Kelley, and Dr. R. Kerber for assistance in drafting portions of this report. This report and its conclusions are, however, solely the responsibility of the Study Group. The names of the members of the Study Group appear in Appendix C.

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## Chapter 2

# SOVIET BALLISTIC MISSILE THREAT: CURRENT AND RESPONSIVE

### CONTENTS

- 2.1 Missile Phases and Kinematics
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  - 2.1.2 Post-Boost Phase
  - 2.1.3 Mid-Course Phase
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- 2.3 Responsive Threat Options
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  - 2.3.2 Booster Rotation and Ablative Shields
  - 2.3.3 Fast Burn Boosters
  - 2.3.4 Post-Boost Vehicle Redesign
  - 2.3.5 Decoys and Penetration Aids
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This chapter presents a review of the phases and kinematics of missile flight, a summary of existing Soviet long range ballistic missile systems, and a discussion of some of the ways the Soviets might redesign their missile forces in response to the deployment of a U.S. ballistic missile defense system. It should be kept in mind that although current Soviet missile deployments provide a useful guide for the *baseline* capabilities which any U.S. ballistic missile defense must achieve, current Soviet deployments are a very uncertain guide for the future given the long time scale for U.S. defensive deployments in even the most optimistic of circumstances.

### 2.1 MISSILE PHASES AND KINEMATICS

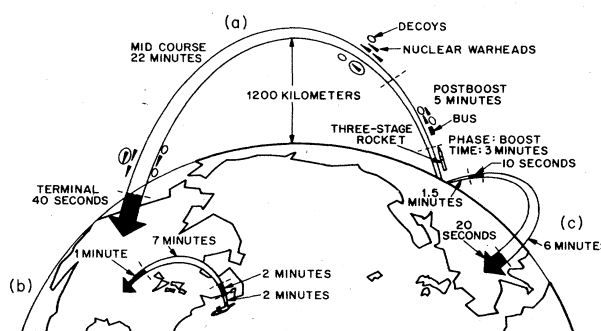
The flight of a ballistic missile may be divided into four phases: boost, post-boost, mid-course, and reentry. This division is natural for the designer of missile systems and equally so for the designer of BMD. For single warhead missiles the post-boost phase is absent, but as we discuss below, in an era of strategic defenses it is likely that even single warhead missiles will employ decoys or other penetration aids and so the equivalent of a post-boost phase will then be present. (Some authors use the term boost phase in a collective sense to include both boost and post-boost phases. For our purposes this is not convenient.)

Figure 2.1(a) shows the trajectory and four phases for a missile with the characteristics of the U.S. MX/Peacekeeper. Figure 2.1(b) shows the same for the SLBM. For an intermediate range ballistic missile like the Soviet SS-20 or the U.S. Pershing II the phases are illustrated in Figure 2.1(c).

#### 2.1.1 Boost Phase

Boost phase begins when the missile leaves its launcher (typically an underground silo for an ICBM and an underwater missile launch tube for a SLBM) and ends when the propulsion motor of the last stage of the booster has shut down and the payload separates from the lifting vehicle. The fundamental idea of staging is to discard empty fuel tanks, large motors, etc. in order to avoid the fuel cost of accelerating parasitic mass to intercontinental range velocities. For ICBMs two or three stages are typically used; for SLBMs two is the norm. In all current Soviet and U.S. strategic (intercontinental range) missile designs, booster burnout occurs well above the sensible atmosphere, but this is not a fundamental requirement. Two examples of existing systems are MX/Peacekeeper (solid fuel)—total boost time 180 s; SS-18 (liquid fuel), the largest of the current generation Soviet ICBMs—total boost time 350 s.

The range of a ballistic missile is determined



**Figure 2.1** (a) Trajectory phases for an ICBM with the characteristics of the U.S. MX/Peacekeeper; (b) trajectory phases for a typical SLBM; (c) trajectory phases for a IRBM. (Illustration reprinted from the September 1985 issue of IEEE Spectrum.)

primarily by the velocity achieved at final booster stage burnout and the angle between the trajectory and the horizontal at burnout. (This angle is called the inclination or reentry angle.) Similarly, total flight time is determined essentially by these same two quantities. The burnout altitude is of secondary importance for either range or total flight time.<sup>1,2</sup>

For a range of 10 000 km, flight times can vary from 28 min to 42 min as the inclination angle is varied from 15° to 35°, respectively. For a solid propellant ICBM flying a 10 000 km range a typical boost phase trajectory sequence is as follows:

Booster component	Burnout time (s) (from launch)	Burnout altitude (km)	Burnout vel (km/s)
Stage 1	60	25	2.5
Stage 2	120	95	4.5
Stage 3	180	250	6.5
PBV	600	≥ 800	7.1

This information represents a composite of typical three-stage ICBM systems with a post-boost vehicle (PBV) capability. Actual performance depends upon the target set and number and weight of deployed objects.

During boost phase the most prominent observable is the infrared (IR) emission from the rocket plume of the missile. This may be readily observed from a satellite at geosynchronous orbit and currently provides the first sign to the U.S. of missile attack. Since the luminosity from the missile plume is so intense, it is impossible to hide the plume in any practical sense. Other signatures which might be exploited by boost phase defenses are the large radar cross section of boosters, visible and ultraviolet emissions from the plume, solar reflection from the missile body (daytime), and, during the atmospheric portion of flight, radiation from shock heated air.

### 2.1.2 Post-Boost Phase

At final stage thrust termination, the booster has given its payload sufficient velocity to reach the desired range. Elements of the payload are now separated from the lifting vehicle and left to fall in ballistic trajectories to impact. In multiple, independently targeted reentry vehicle (MIRV) systems small velocity increments are given to each reentry vehicle (RV) to direct them to individually designated targets.

Although details differ, the Soviets have adopted the basic approach to independent targeting that was pioneered by the United States. Namely, an additional missile stage, called the bus or post-boost vehicle, is employed. The bus needs to have an inertial guidance system, thrusters (rockets), and a thrust control system; it carries RVs, and, if defenses are present the bus can be used also to carry and dispense decoys and other penetration aids. As its name implies, the bus releases RVs singly as preprogrammed velocities (and positions)

are reached. Thrusters on the bus may burn continuously or intermittently. In addition to permitting independent targeting, the presence of a post-boost stage enables corrections to be made for errors accumulated in boost phase and boost thrust cutoff, thus improving overall accuracy.

Although conceptually the post-boost vehicle is just another rocket stage, in design and observable characteristics it is quite distinct. Whereas booster stages produce a net velocity appropriate to intercontinental range (6–7 km/s), the bus stage typically imparts much smaller velocity changes per RV on the order of 0.5 km/s or smaller. The PBV may carry enough propulsion fuel to give a total velocity change  $\Delta V = 2\text{--}3$  km/s. Typically this will be expended in transverse and longitudinal maneuvers.

The key advantage of current bus designs over other possibilities for independent targeting of multiple warhead missiles is that only a single inertial guidance and thruster system is required on each bus and within the limitations set by fuel, space, and missile throw-weight, any number of RVs can be accommodated. It is clear that the bus concept is ideal in many ways also for the release of decoys and other penetration aids in a world of missile defenses.

Observables in post-boost phase are generally much weaker than in boost phase. Sizes, masses, and radar cross sections of the objects of interest are smaller; IR emissions from the PBV thruster plume are orders of magnitude smaller than for the final booster stage (cold gas thrusters on the PBV can reduce this even further); and the number of potential targets to be tracked and designated by the defense grows steadily throughout the PBV phase. At the beginning of the post-boost phase, the bus is a high value target equal to the booster itself. As deployments ensue, the value of the bus steadily diminishes until the release of the last RV when the value of the bus goes to zero.

### 2.1.3 Mid-Course Phase

For all but tactical missiles, mid-course is the longest of the trajectory phases. Throughout mid-course all the RVs and decoys, as well as bus and booster remnants (the "threat cloud") from a given missile move along nearby ballistic trajectories (the "threat tube") under the influence of gravity; light and heavy objects move alike. The mid-course phase ends at reentry when objects in the threat cloud experience drag forces in the upper atmosphere sufficient to cause observable deviations from ideal ballistic trajectories.

The relatively long length of the mid-course phase ( $\approx 20$  min for intercontinental range) can be advantageous to the defender, since several minutes can be devoted to establishing track files as well as performing a discrimination function. Moreover, there is sufficient time for the defender to choose when to attack, to allow

additional satellites to come into the battle space, and to revisit objects for follow-up attack or kill assessment. On the other hand, there are many disadvantages to the defender in mid-course. The number of objects is greatly increased over that of boost phase and early stages of the post-boost phase, and the high leverage of boost phase and post-boost phase kill of MIRVed missiles is lost. Once deployed RVs tend to be much harder targets than are boosters and post-boost vehicles. Special discrimination opportunities provided by observing post-boost vehicle maneuvering and releases are no longer present, and mid-course signatures are generally few and weak relative to those present in all other phases of missile flight. Most significantly, because atmosphere drag is totally absent in mid-course, the offense can employ lightweight decoys which match the rigid body dynamics of massive RVs and the external observables of RVs as well.

### 2.1.4 Reentry Phase

Many of the taxing discrimination problems associated with mid-course defenses disappear or are greatly relaxed once reentry ( $\approx 130$  km altitude) has occurred. Atmospheric drag not only produces changes in trajectory, it also increases the optical signature of reentering bodies through frictional heating. All these effects provide tracking and discrimination opportunities. However, these opportunities are offset by the short times (typically less than 60 s) available to a terminal defense for tracking and for committing interceptors, and by the opportunity the offense has to perturb vast portions of the defenders field of view by nuclear precursor bursts. For these reasons terminal defenses are most attractive for hard sites (missile silos, underground command and control centers, etc.) and least attractive for city and population defense. Directed energy weapons are not currently viewed as playing a significant role in terminal defenses. Instead nuclear or kinetic energy weapons are favored; for these reasons we do not discuss the use of DEWs in terminal defenses in this report.

### 2.1.5 Trajectory Options

The trajectories shown in Figures 2.1(a)–2.1(c) are so-called minimum energy trajectories.<sup>1,2</sup> For given launch and target points, they are the paths which maximize payload to the target for a given missile type, or equivalently, maximize the range to which a given missile can deliver a fixed payload. In a flat earth approximation (uniform gravity) with no atmospheric drag, minimum energy trajectories would be parabolic and have a  $45^\circ$  elevation above the horizon.

When the effects of the curvature of the earth and the  $1/r^2$  decrease of the gravitational acceleration with distance from the earth's center are included but thrust and drag are neglected, a ballistic trajectory is a portion of

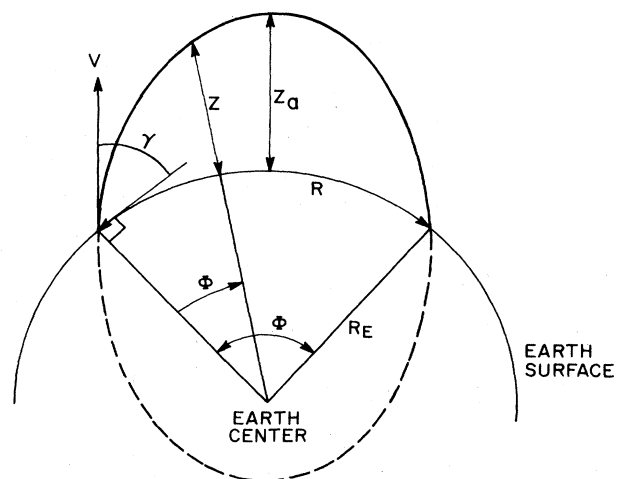
an ellipse making an angle  $\gamma$  with the tangent plane to the earth at the launch and target points. As remarked above,  $\gamma$  is called the inclination reentry angle. For the minimum energy trajectory,

$$\gamma_m = (\pi - \Phi) / 4,$$

where  $\Phi$  is the range angle, i.e., the angle subtended at the earth's center by rays through the launch and target points; see Figure 2.2. For a typical intercontinental range,  $R = 10\,000$  km,  $\Phi = 90^\circ$ , and so  $\gamma_m = 22.5^\circ$ . Atmospheric drag causes departures from an elliptic trajectory in the reentry phase; drag and thrust do the same during boost phase. By sacrificing range and/or payload one can employ lofted trajectories ( $\gamma > \gamma_m$ ) or depressed trajectories ( $\gamma < \gamma_m$ ). Figure 2.3 shows some examples for an intercontinental missile.

Lofted trajectories have increased flight time over the minimum energy trajectories and have greater velocities at burnout and impact. Except perhaps against terminal defenses which would be stressed by increased reentry velocities, lofted trajectories, or defense evasion techniques such as maneuvering RVs which exploit the presence of an atmosphere, do not appear to be a likely offense choice in the face of multitier missile defenses. However, since during boost phase they exit the atmosphere earlier than a minimum energy trajectory, lofted trajectories might conceivably have an advantage in that decoy release could be effected earlier; this is not likely to be significant.

Depressed trajectories, on the other hand, offer some attractive possibilities to the offense. A depressed trajectory shortens total flight time; it also increases the time a missile spends within the atmosphere and is therefore unreachable by weapons for which the



**Figure 2.2** The elliptical trajectory of a missile flight in the approximation in which boosting is impulsive and atmospheric drag is neglected. The range angle is  $\Phi$  and the reentry angle  $\gamma$ .

## ICBM 9000 km RANGE FOR 15 deg, 24 deg, 35 deg, 40 deg TRAJECTORIES

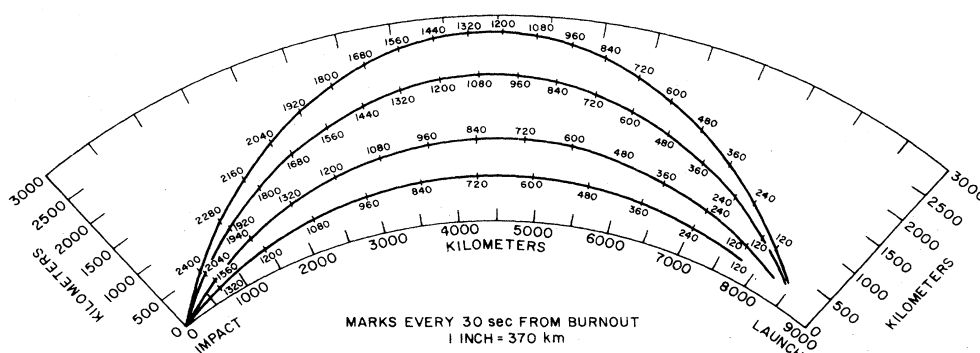


Figure 2.3 Minimum energy, lofted, and depressed trajectories for an ICBM.

atmosphere is opaque, and increases the amount of time the missile is below the earth's horizon as seen by a given satellite of the defensive system. Nevertheless, there are drawbacks to depressed trajectories. They result in decreased range, cause some loss in ballistic accuracy because of unpredictable atmospheric perturbations, and impose a delayed release of decoys compared to minimum energy trajectories. In addition, because of higher re-entry velocities, RV heating is greater for depressed trajectories, a limitation on this option.

Another major drawback of depressed trajectories, reduced range at fixed payload, is probably least serious for SLBMs, since submarines have the option of moving closer to a target before launch. Also, since SLBMs currently are less accurate than ICBMs, small additions to missile inaccuracies are less significant. While neither the United States nor the Soviet Union has shown much interest in depressed trajectories to date, the situation could change rapidly in an era of ballistic missile defenses.

## 2.2 CURRENT BALLISTIC MISSILE FORCES

Figure 2.4 gives current American and Soviet ICBM deployments.<sup>3,4</sup> The Soviets have approximately 1400 land-based strategic ballistic missiles, carrying a total of 6200 RVs. The bulk of these are of the SS-17, SS-18, and SS-19 types which together represent virtually all of the high accuracy ICBM RVs in the current Soviet inventory. All of these Soviet ICBMs are deployed in hardened underground silos, many of which have been upgraded since 1972. While these missiles are not invulnerable to attack by high accuracy nuclear weapons, it is noteworthy when thinking about future developments that the rate of upgrading of the ICBMs and silos has been more rapid than in the U.S. program. One should also note that in spite of the difference in modernization rates, the qualitative status of U.S. and Soviet ICBM systems is similar. The Soviets are thought to have a slight lead in

silos; hardness; the U.S. is ahead in solid propellant technology and in accuracy.

As indicated by the "Mod" numbers in Figure 2.4, a given Soviet missile type (especially its post-boost stage) typically goes through evolutionary changes. About 580 of the current Soviet ICBMs are members of the older SS-11 and SS-13 classes. The SS-16 shown in Figure 2.4 is an early design solid-fuel missile which the Soviets agreed not to deploy under the terms of the SALT II agreement. The upper two stages of the SS-16 constitute the basis of the SS-20 missile currently deployed in various parts of the Soviet Union.

Soviet ICBM research and deployment is a dynamic, ongoing process carried out<sup>5</sup> in several design bureaus under the Ministry of General Machine Building (GMB). At least two new generation ICBMs are in early deployment phases and others are reported under development.<sup>3</sup> One of the new systems, designated in the West as the SS-24, is similar to the U.S. MX/Peacekeeper: 10 RVs, three stages, solid fuel. It is speculated<sup>5</sup> that initial SS-24 deployments will be in silos and later deployments rail-mobile. The second newly deployed land mobile Soviet missile, the SS-25, is about the size of the U.S. Minuteman and appears to be the Soviet version of the single warhead, land-mobile missile which is in the early stages of development in the U.S. (unofficially, Midgetman). The SS-24 and SS-25 missiles and subsequent follow-on Soviet ICBMs can be expected to have improved accuracy and improved survivability. The move to increase use of solid propellants by the Soviets is likely to continue.<sup>3</sup>

From the European perspective, several other missile types are relevant. Some of these, the so-called longer range, intermediate range ballistic missiles (LR-IRBMs),<sup>3,4</sup> are shown in Figure 2.5. All U.S. and Soviet Union intermediate range missiles have unhardened basing; most are land-mobile. Not illustrated in Figure 2.5 are French land-based missiles, numerous shorter range U.S., Soviet, and People's Republic of China missiles, and tactical nuclear weapons.



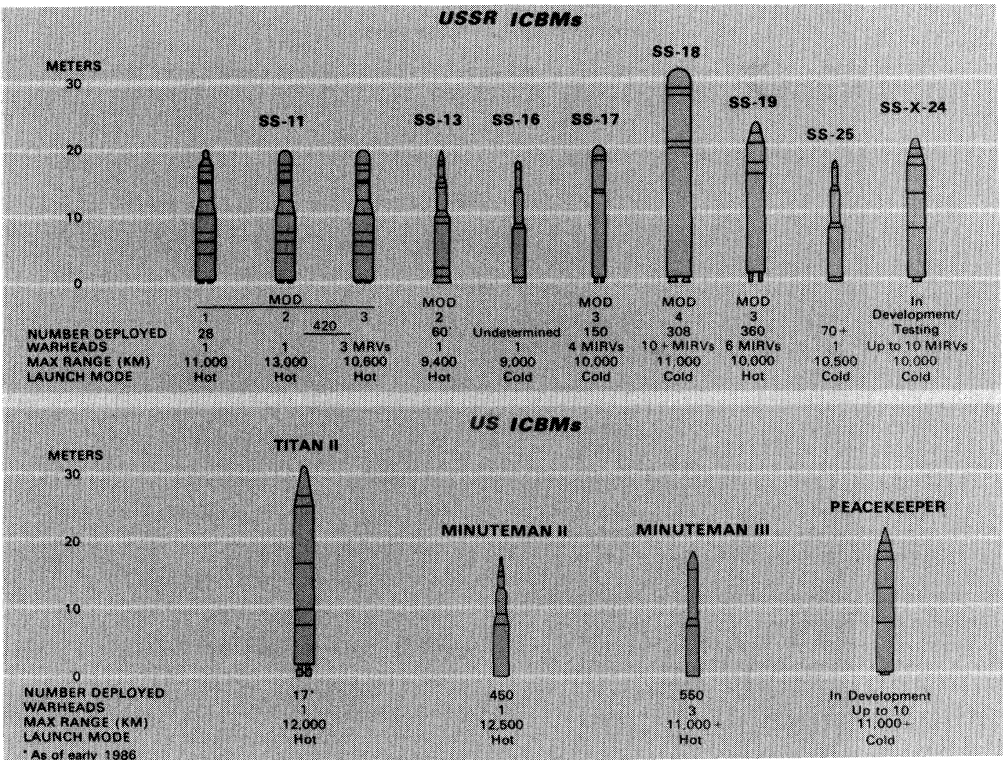


Figure 2.4 U.S. and Soviet ICBM deployments.

Soviet and American SLBM deployments<sup>3,4</sup> are shown in Figure 2.6. Not shown on the U.S. side is the Trident II (D-5) missile currently under development. It will have a range comparable to the Trident I (C-4) missile but will have greatly enhanced accuracy. Also not shown in Figure 2.6 are the considerable British and French SLBM deployments.

Soviet SLBM deployments currently number about 928 strategic missiles aboard 62 nuclear powered submarines, many of recent vintage. Eighteen of these submarines (carrying 300 launchers) are fitted with

MIRVed missiles. These latter constitute about 1400 RVs out of a total of 2100 Soviet submarine-based RVs. The Soviets also currently maintain 13 diesel powered submarines capable of firing nuclear missiles.

As with ICBMs, Soviet SLBM and submarine development is carried out<sup>5</sup> by specialized, ongoing design bureaus under the Ministry of GMB. It is anticipated<sup>3</sup> that the Soviets will be testing versions of the SS-N-20 and SS-NX-23 in the near future. One can expect new types of Soviet SLBMs as well, and expect them to have greater accuracy and perhaps greater throw-weight than current

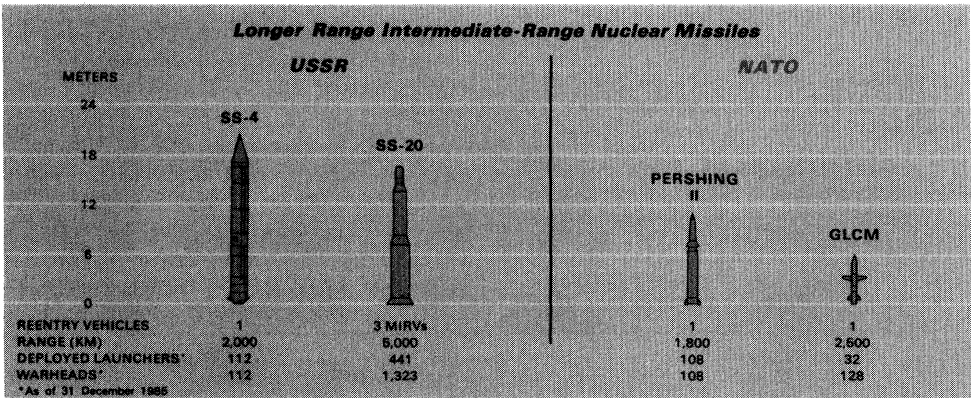


Figure 2.5 U.S. and Soviet LR-IRBM deployments.

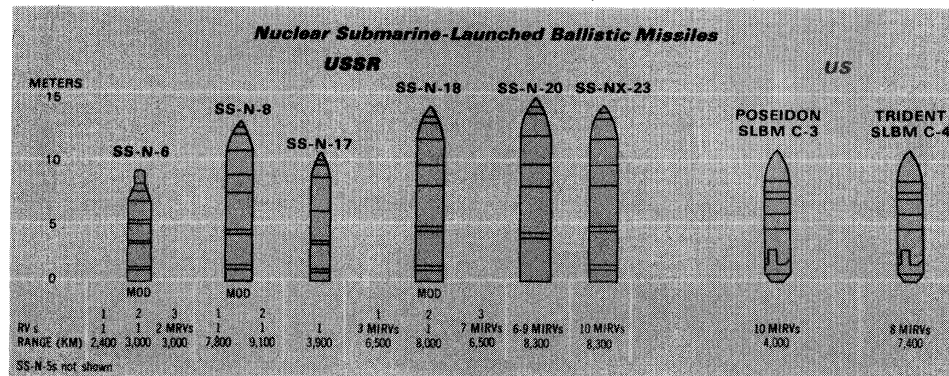


Figure 2.6 U.S. and Soviet SLBM deployments.

designs. Since the Soviets have historically depended more extensively on their land-based ICBMs and since Soviet ballistic missile submarines spend less time “on station” than their U.S. counterparts, it is likely that any shifts in Soviet deployment percentages, land-based versus sea-based, will occur only slowly.

### 2.3 RESPONSIVE THREAT OPTIONS

In thinking about how the Soviets might respond to a U.S. deployment of multilayered ballistic missile defenses several points are worth keeping in mind.

- (i) A large number of years will be required to develop and deploy defenses; hence considerable time will be available to the offense to plan and execute responses. As a base for response, the Soviets have large, ongoing missile programs.
- (ii) A complete defense architecture has not yet been defined by the U.S.; therefore, it is not possible (even for the Soviets) to make specific predictions regarding responses.
- (iii) It is nevertheless important to analyze possible responses now since such analyses can aid in identifying those defensive technologies and architectures which are most and least attractive. It is necessary, moreover, to do such studies in order to gain an understanding of the relative difficulty (technology level, effectiveness, cost, lead time) of deploying defenses versus deploying offensive responses. A single response to U.S. defensive deployments would lack the high probability of success and reliability which the Soviets seek in their deployments. Thus, it is most likely that they will react in many ways simultaneously, by spreading their responses across the range of forces on which they currently rely, and also by introducing new systems as well.

Some possible Soviet responses are the following:

- Capability for direct attack of defense components

- Offensive proliferation
- Booster rotation and ablative shields
- Fast burn boosters
- Post-boost vehicle redesign
- Decoys and penetration aids

The above list of possible Soviet responses is illustrative and by no means inclusive. The first item above, direct attack (also called defense suppression), is so important that we treat it as the subject of a separate chapter (Survivability, Chapter 9). The importance of this subject is further underscored by the fact that survivability is the first of the “Nitze Criteria”<sup>6</sup> for deployment of a U.S. defensive system. The remaining responses in the above list are treated in the subsections which follow. Clearly, a thorough understanding of the feasibility of these latter responses and an analysis of the financial cost and performance penalties these would extract from the offense is necessary before a judgment can be made on the efficacy of any proposed U.S. missile defense system. A succinct statement of this is the other of the “Nitze Criteria,”<sup>6</sup> namely defensive deployments must be “cost-effective at the margin.”

#### 2.3.1 Offensive Proliferation

A common prediction for the response of the Soviets is that they will simply build more offensive boosters and RVs. That is the approach the U.S. took in the 1960s and 70s partly in response to a prospective Soviet ABM. The U.S. fractionated both ICBM and SLBM missile payloads and deployed RVs in far greater numbers than were predicted for Soviet interceptors. This approach, defense exhaustion, has to date been judged to be cost effective when dealing with a defense whose number of potential intercepts is known. This response is also consistent with past Soviet responses, in which they have demonstrated an inclination toward continuing to rely on existing military forces, and on improving them incrementally.

For some but not all DEW-based defenses, the

requirements for exhaustion may not be easily determined by the offense. In the case of chemical lasers the total kill potential of a satellite laser battle station is quantifiable by viewing fuel supplies. For ground-based FELs and for x-ray lasers this is not so easily done. Whatever the case, if there is no boost phase intercept capability, offensive proliferation will be highly attractive.

Indicative of the missile production capability of the Soviets is 1985 testimony before the Senate Armed Services Committee by Gates and Gershwin,<sup>7</sup> "By the mid-1990s, nearly all of the Soviets' currently deployed intercontinental nuclear attack forces—land- and sea-based ballistic missiles and heavy bombers—will be replaced by new and improved systems. New mobile intercontinental ballistic missiles (ICBMs) and a variety of cruise missiles are about to enter the force. The number of deployed strategic force warheads will increase by a few thousand over the next five years, with the potential for greater expansion in the 1990s." In considering what might happen in the absence of arms control constraints these analysts went on to say,<sup>7</sup> "While the Soviets would not necessarily expand their intercontinental attack forces beyond from 12,000 to 13,000 warheads in the absence of arms control constraints, they clearly have the capability for significant further expansion, to between 16,000 and 21,000 deployed warheads by the mid-1990s. The lower figure represents a continuation of recent trends in deployment rates; the upper figure is not a maximum effort but would require a substantially greater commitment of resources."

Similarly, the Department of Defense Publication *Soviet Military Power 1986* indicates<sup>3</sup> that by the mid-1990s, many of the current Soviet ICBMs will be retired and the deployed mix will consist of SS-19s, SS-24s, SS-25s, and a set of new heavy missiles (yet unnamed) as replacements for the SS-18s. Less dramatic but substantial changes are also predicted for Soviet SLBM forces. These Soviet modernization programs represent changes undertaken before any stimulus of possible U.S. missile defenses. There is ample evidence that the targets of tomorrow's U.S. strategic defenses are not today's Soviet offensive forces; instead the U.S. will face a responsive threat from the very beginning.

### 2.3.2 Booster Rotation and Ablative Shields

If the boost phase intercept employs thermal kill lasers which require long kill times (tenths of seconds or longer), a low technology countermeasure is booster rotation. Rotation of missiles at angular rates of the order of 1 rps have been studied and shown to extract little or no penalty to the offense. It is likely that missile rotation could be accomplished on a retrofit basis.

Rotation increases kill times by spreading the laser energy over an increased booster surface area. Although any amount of rotation works against the defense,\* to get

the maximum effect from this countermeasure the offense needs to make the rotation period less than the kill time. We call this optimal rotation. Consider the situation of optimal rotation and a normally incident laser beam with no aiming error. Let the radius of the laser spot at the booster be  $a$  and the booster be a cylinder of radius  $R$ . There are two interesting cases: (1)  $a > R$  and (2)  $a \ll R$ . In analyzing either case it is important to keep in mind that while the laser beam illuminates a large area on the booster, typically  $1 \text{ m}^2$  or more, the lethal fluence needs only to be achieved over a smaller area, say 30 cm in diameter, for kill to be accomplished. Failure occurs at the spot at which the integrated power first reaches lethal fluence. Under our assumptions of zero aiming and tracking error, this will occur along the missile centerline.

First consider the large beam case (1) and examine a vertical slice of the booster of height  $\Delta z$  taken at the center of the laser spot. It intercepts a transverse area of the beam

$$A_1 = 2R\Delta z. \quad (2.1)$$

With optimal rotation the intercepted laser energy in the slice is spread over a booster area of

$$A_B = 2\pi R\Delta z \quad (2.2)$$

and kill time is increased by the ratio

$$\frac{t_k(\text{rot})}{t_k(0)} = \frac{A}{A_1} = \pi. \quad (2.3)$$

Next consider the small beam case (2). The beam spot on the booster has area  $\pi a^2$ . Assuming the defense keeps this spot fixed on the booster centerline and that optimal rotation is employed by offense, the energy in the laser spot is spread over a total booster area of  $4\pi Ra$  (thermal conduction and reradiation are ignored). Hence kill time is increased according to

$$\frac{t'_k(\text{rot})}{t_k(0)} = \frac{4\pi Ra}{\pi a^2} = 4 \left[ \frac{R}{a} \right] > 4. \quad (2.4)$$

Hot spot tracking has been suggested as a means for the defense to counter booster rotation. It should be noted that hot spot tracking is applicable only to case (2) and that even in this case booster rotation increases kill time since the beam will not remain normal to the booster surface and eclipsing will occur if missile failure is not achieved before the hot spot rotates to the back side of the missile. For a sufficiently high rate of rotation eclipsing will always occur and kill time is increased by a factor of  $\pi$  (thermal conduction and reradiation are ignored) as in case (1). Hot spot tracking places heavy burdens on the defense since it must achieve beam spot sizes small compared to missile diameters and in addition have the capability to sense and track the hot spot in a dynamic environment; in contrast, the offense must only achieve a certain rate of booster rotation. We see that booster rotation must be assumed if thermal kill lasers are used, since the offense can always enforce an increase in kill time by at least a factor of  $\pi$ . Booster rotation has no

\*Assuming a minimum spot size criterion has been met.

effect on impulse kill directed energy weapons.

Less discussed is rotation of post-boost vehicles. Here the attractiveness to the offense of rotation is less clear since the PBV must make precision deployments of RVs and decoys during its lifetime. These tasks are likely to be complicated by PBV rotation. For RVs there can be no doubts. To achieve stability in atmospheric reentry, all modern missile systems employ some means of spinning up RVs before or after release from the PBV; in short, RVs already spin.

In addition to rotation, boosters can be further hardened against lasers by the addition of a layer of ablative material on exterior surfaces. This, too, is a relatively simple countermeasure and can probably be done on a retrofit basis; a throw-weight penalty is involved. Alternatively, if the offense chooses to introduce a totally new missile design, either in response to a ballistic missile defense or in the regular course of a modernization program, it can select a slightly larger missile than the one being replaced and retain the previous throw-weight while including ablative coatings.

Since there has been controversy<sup>8</sup> concerning the penalties for retrofitted ablative shielding, we present here a detailed discussion with emphasis on the basic physical principles involved. Our numbers are not intended to reflect serious engineering design. The reader is referred to the discussion of heats of ablation in Chapter 6 to learn what level of protection a given mass per unit area of ablator provides against thermal laser attack.

We note first that the missiles of interest are all multistage so the question of what stages need hardening must be discussed first. If we take the three-stage missile described in the table above which shows first stage burnout at 25 km, it is clear that the offense would have no need to harden the first stage if the defense was using weapons unable to penetrate to this depth in the atmosphere, e.g., x-ray lasers, HF chemical lasers, short wavelength impulse kill lasers (having short pulse duration), and neutral particle beams. Even if the defense could penetrate below first-stage burnout altitudes, the offense could still forego first-stage hardening if defense response times exceed first-stage burnout time (60 s in the example above but much less for the fast burn booster designs discussed below). Similarly, one may or may not need to harden the second stage of a multistage booster depending on burnout time and defensive weapon characteristics and response time.

For algebraic simplicity we consider a two-stage missile with a post-boost vehicle which we will refer to as the payload. This payload consists of PBV structural components and equipment, PBV fuel, RVs, and decoys. The formulas presented below are easily generalized to the three-stage case. We begin with the case of no shielding and write the mass of the first stage as  $m_1 = m_{s1} + m_{p1}$  and the mass of the second stage as  $m_2 = m_{s2} + m_{p2}$  where  $m_{p1}$  and  $m_{p2}$  denote propellant masses and  $m_{s1}$  and  $m_{s2}$  denote "dry" stage masses (i.e., shell, empty propellant tanks, rocket motors, etc.). Except for rocket engines and a few

small components, it is a good approximation to assume that structure masses scale with propellant masses so we may write  $m_{s1} = \alpha_1 m_{p1}$  and  $m_{s2} = \alpha_2 m_{p2}$  where  $\alpha_1$  and  $\alpha_2$  are "tankage" factors. Typically for solid fuel rockets  $\alpha = 0.10$ , whereas for liquid fuel missiles  $\alpha = 0.15$ .

The rocket equation with the gravity term ignored gives for the total velocity increment,

$$\begin{aligned} \Delta v_{\text{tot}} &= g I_{\text{sp}1} \ln \left\{ \frac{m_1 + m_2 + m_{p0}}{m_{s1} + m_2 + m_{p0}} \right\} \\ &\quad + g I_{\text{sp}2} \ln \left\{ \frac{m_2 + m_{p0}}{m_{s2} + m_{p0}} \right\} \\ &= g I_{\text{sp}1} \ln \left\{ \frac{(1 + \alpha_1)m_{p1} + (1 + \alpha_2)m_{p2} + m_{p0}}{\alpha_1 m_{p1} + (1 + \alpha_2)m_{p2} + m_{p0}} \right\} \\ &\quad + g I_{\text{sp}2} \ln \left\{ \frac{(1 + \alpha_2)m_{p2} + m_{p0}}{\alpha_2 m_{p2} + m_{p0}} \right\}, \end{aligned} \quad (2.5)$$

where the first logarithm on the right-hand side of Eq. (2.5) represents the velocity contribution from stage 1 and the second logarithm that from stage 2. The quantities  $I_{\text{sp}1,2}$  are the specific impulses of the rocket fuel; they are related to the exhaust velocities of the two stages according to  $v_e = g I_{\text{sp}}$  where  $g$  is the acceleration of gravity at sea level. In Eq. (2.5)  $m_{p0}$  is the payload (without shielding).

If the tankage factors and specific impulses of the two stages are equal, optimal staging (minimum propellant to deliver the payload to a given range) occurs when the velocity increments of the two stages are equal. It follows that

$$\frac{m_{p2}}{m_{p0}} = \frac{E - 1}{1 - \alpha(E - 1)}, \quad (2.6)$$

$$\frac{m_{p1}}{m_{p2}} = \frac{E}{1 - \alpha(E - 1)}, \quad (2.7)$$

where

$$E \equiv \exp \left[ \frac{\Delta v_{\text{tot}}}{2g I_{\text{sp}}} \right]. \quad (2.8)$$

As a numerical example consider a "nominal" SS-18 with  $m_{p0} = 8000$  kg (i.e., 8 tonnes),  $\alpha = 0.15$ ,  $\Delta v_{\text{tot}} = 7$  km/s,  $I_{\text{sp}} = 306$  s. The above equations give stage masses  $m_1 = 146.2$  tonnes,  $m_2 = 30.4$  tonnes, a gross (liftoff) mass  $M_0 = m_1 + m_2 + m_{p0} = 184.6$  tonnes, and an exhaust velocity  $v_e = 3$  km/s.

Now add shielding as a retrofit. The propellant and structure masses of the two stages remain fixed and so also does  $\Delta v_{\text{tot}}$  since we are supposing the same range. To achieve this same final velocity after adding shielding, the payload is reduced to  $m_p$  and is the quantity we wish to calculate. It is obvious that any shielding added to the PBV will subtract from the useful payload on a kilogram-for-kilogram basis. Recognizing this, it is

technically convenient to discuss the case of no PBV shielding and then subtract by hand the effect of such shielding.

Denoting the mass of the ablative shields as  $m_{a1}$  and  $m_{a2}$  on stages 1 and 2, respectively, the corresponding rocket equation follows by making the substitutions  $m_{s1} \rightarrow m_{s1} + m_{a1}$ ,  $m_{s2} \rightarrow m_{s2} + m_{a2}$ , and  $m_{p0} \rightarrow m_p$  in Eq. (2.5). Because the payload and mass of the second stage shield enters only in the combination  $m_{a2} + m_p$  we see immediately that the second stage shielding also subtracts from payload on a kilogram-for-kilogram basis. Physically this is obvious since the second stage shield is carried to the final payload velocity before being discarded. We may express this as

$$-\left[ \frac{\partial m_p}{\partial m_{a2}} \right]_{m_{a1}} = 1. \quad (2.9)$$

Rather than treating the general case explicitly which

$$\frac{[(1+\alpha+\sigma)m_{p1} + (1+\alpha+\sigma)m_{p2} + m_p] [(1+\alpha+\sigma)m_{p2} + m_p]}{[(\alpha+\sigma)m_{p1} + (1+\alpha+\sigma)m_{p2} + m_p] [(\alpha+\sigma)m_{p2} + m_p]} = E^2 \quad (2.10)$$

along with Eq. (2.8). The quantity  $\sigma$  is in turn specified in terms of total shielding mass according to

$$\sigma = m_a / (m_{p1} + m_{p2}). \quad (2.11)$$

Although Eq. (2.10) could be solved algebraically for  $m_p$ , the results are not particularly illuminating. However, the derivative of the payload versus shielding at the origin has a simple form

$$-\left[ \frac{\partial m_p}{\partial m_a} \right]_{m_a=0} = \left\{ 1 - \frac{1}{\left[ 1 + \frac{1-\sigma(E-1)}{E} \right]} \frac{1}{\left[ 1 + \frac{1-\sigma(E-1)}{1+\sigma(E-1)^2} \right]} \right\} < 1. \quad (2.12)$$

After solving Eq. (2.10) and substituting numerical parameters appropriate to the nominal SS-18 introduced above, we obtain the curves shown in Figure 2.7.

Physically the finding that a given mass of shielding distributed over both stages reduces the payload differentially by less than a factor of one reflects the fact that first stage shielding is not carried to the final payload velocity.

If we assume the total surface area of our nominal SS-18 is 300 m<sup>2</sup> and that 2 g/cm<sup>2</sup> of shielding is added, the net shielding mass will be 6 tonnes. Proportioning this according to stage masses, we have 4.75 tonnes on the first stage, 0.99 on the second, and 0.26 on the PBV. From Figure 2.7 the payload reduction corresponding to a first and second stage shield of 5.74 tonnes is 1.74 tonnes. To this we must add the 0.26 tonne PBV shield; the net payload reduction is 2 tonnes.

It is incorrect to assume this payload reduction must be met by RV offload alone. The PBV carries fuel as well as RVs (and perhaps decoys). With fewer RVs on board, less RV fuel is required to achieve the same footprint. Furthermore, when faced with the challenge of penetrating a missile defense, the offense may well be

is algebraically tedious, it is convenient to consider the case where the ablative shield masses scale according to  $m_{a1} = \sigma m_{p1}$ ,  $m_{a2} = \sigma m_{p2}$ . With the answer to this case in hand and the answer for second stage shielding alone one can readily calculate the payload reduction for any mix of first and second stage shielding.

The appropriate rocket equation for retrofitted shielding with first and second stage shielding and equal tankage factors may be obtained from Eq. (2.5) by the substitution  $\alpha \rightarrow \alpha + \sigma$  and  $m_{p0} \rightarrow m_p$ . Note, however, that one cannot make the same substitutions and use Eqs. (2.6) and (2.7) since these apply to optimal staging in the absence of shielding. After adding shielding on a retrofit basis, staging will not remain optimal—the two stages will give unequal increments to the net velocity. Only if one considers a new missile with shielding and optimal staging can Eqs. (2.6) and (2.7) be used.

For a retrofit shielding, the equation which determines  $m_p$  as a function of  $\sigma$  is

willing to adjust its targeting to accommodate smaller footprints, sacrificing PBV fuel in favor of an increased number of RVs and decoys.

Going back to our example, suppose that the original 8 tonne PBV mass consisted of 10 RVs each of about 300 kg, an equal mass of fuel, and 2000 kg of PBV structure.

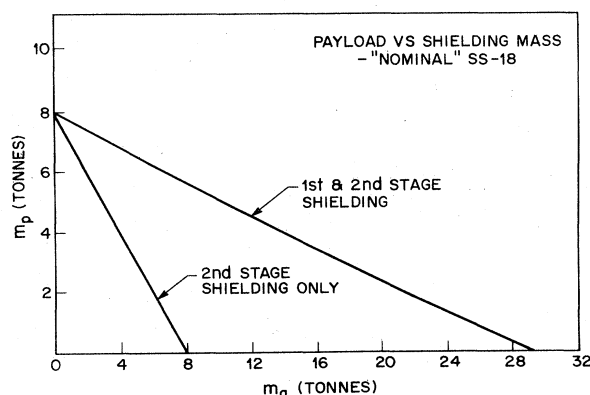


Figure 2.7 Payload reduction as a function of ablator shield mass for a "nominal" SS-18. See text for the assumptions which apply to the various cases.

For a 2 tonne payload reduction dictated by the addition of 6 tonnes of ablator, equipartition between RV and fuel offloads results in a net reduction of 3 RVs. Not included in any of our considerations thus far is another option. The offense could accept a reduced second stage burnout velocity and use PBV fuel to make this up. Whether or not this permits a greater number of RVs to be carried to range depends on details such as the specific impulses of the booster and PBV fuels, missile tankage factors, etc. Additionally, the offense might redesign just the PBV stage (four models of the SS-18 PBV have already seen service) to reduce structure weight in response to the fact that the PBV will be carrying a reduced number of RVs. This might permit the retention of an additional RV which would otherwise have to be offloaded. In any case, it is clear that calculations of RV reductions required by retrofitting ablative shielding often have hidden assumptions. The offense has many options all of which must be explored before final conclusions can be drawn.

### 2.3.3 Fast Burn Boosters

Because of the high leverage of boost and post-boost phase defenses and because of the greater opportunity to employ decoys once these phases are passed, it is likely that the Soviet response will be strongly conditioned by its perceived capability of U.S. defenses in these first two phases. Current ICBMs have not been designed to cope with boost phase defenses. As a result the boost phase is quite long—typically 3 to 6 minutes, and the burnout altitude is high—typically 200 to 300 km. By the same token, the pace of typical post-boost phases is leisurely and may take a minute or so to place each reentry vehicle (and penetration aid) on its proper trajectory. The SS-18, for example, has a total time from liftoff to completion of post-boost phase of 10 min. Studies<sup>9</sup> conducted during the past few years have concluded that boost and post-boost phases need not be so time consuming. Through the use of modern solid rocket propellants with grain configurations designed for rapid burn, ICBM-range boosters that complete their burn in less than one minute at altitudes of 80 to 100 km appear feasible. There appear to be no physical barriers to such performance; the only issues are one of engineering tradeoffs.

Although an intercontinental range fast burn booster (FBB) would represent a significant new development, the offensive penalty in terms of throw-weight appears to be small. Studies<sup>9</sup> performed by McDonnell Douglas Corporation and Martin Marietta in 1983 in support of the Fletcher (DTST) Study indicated that a solid propellant ICBM capable of burning out in 60 s at an altitude of 80 km was feasible. The associated payload reduction was found to be approximately 20% assuming the same launch weight for the FBB as for a conventional solid booster. More recent and comprehensive work performed at Lockheed<sup>10</sup> which included an analysis of staging, exit heating, interstage structures, and

controllability gives similar indications. Figure 2.8, adapted from the Lockheed study, shows throw-weight as a function of booster burntime. The 1983 analyses cited in Reference 9 also concluded that there need be no payload reduction at all associated with fast burn boosters if the overall launch weight is allowed to grow by 15–20 %.

Two things are noteworthy at this point. First, an important step toward a fast burn booster is that of using a solid propellant; that step is one already being taken by the Soviets in their SS-20, SS-24, and SS-25 systems. The Soviets are judged to be behind the U.S. in solid propellant technology, but it is not clear that this will be a permanent state of affairs. Second, it is important to note that the term “fast burn booster” can be misleading. What is required for intercontinental velocities at a burnout altitude of 80–100 km is a peak acceleration of 30–40 g versus the 8–15 g levels typical of current boosters. This difference does not represent a drastic change. In particular it does not call for technologies associated with very high acceleration boosters such as the 1960s vintage SPRINT or Spartan interceptors, or for that matter, with modern Soviet ABM interceptors. Of course, fast burn boosters alone are not a fully responsive offensive countermeasure. The offense would want to minimize the total time to completion of RV deployment as well. We discuss rapid post-boost deployments below (Section 2.3.4).

The consequences of a fast burn booster (FBB) response are far reaching:

- (i) Space-based x-ray lasers (XRL) cannot penetrate into the atmosphere to altitudes below about 80 km. Hence, FBBs remove booster intercept from XRL missions.
- (ii) Space-based neutral particle-beam (NPB) weapons also cannot penetrate into the atmosphere to altitudes below about 120 km. Hence, FBB removes booster intercept from NPB missions.
- (iii) The FBBs short burn time also taxes weapons that are capable of penetrating into the atmosphere

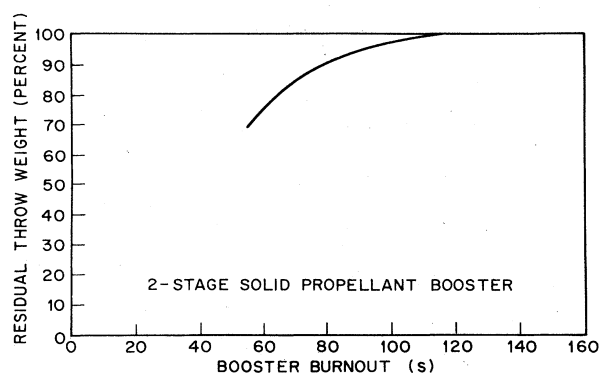


Figure 2.8 Fast burn booster performance: throw-weight penalty vs booster burn time. (Adapted from Lockheed, Ref. 10.)



(space-based and ground-based lasers, and kinetic energy weapons) simply because the engagement of simultaneously launched boosters must be completed in a few tens of seconds. This places extreme demands for short retarget time, kill time, and/or increase the number of battle stations required to cope with a given size attack.

- (iv) A FBB response would almost certainly make pop-up defense against the boost phase unreasonable due to the short time available for the battle.

### 2.3.4 Post-Boost Vehicle Redesign

While fast burn boosters pose severe problems for a defense seeking to kill the booster itself, the offense is not necessarily "home free" against DEWs or other defenses employed in the post-boost phase.

With a FBB burnout altitude of approximately 80 km, the offense is faced with problems if it plans to deploy lightweight decoys. There is enough atmosphere at such altitudes to result in differential deceleration of heavy reentry vehicles and lightweight decoys. This difference could allow the defense elements to discriminate RVs from decoys, something the offense would wish to avoid. Figure 2.9 illustrates this problem and shows that if, for example, the defense is given credit for acceleration measurements of  $10^{-2}$  g, the offense would need to delay deployment from the PBV until an altitude exceeding 120 km was reached. This implies the need for a coast phase in the interval between booster burnout and the time RV/decoy releases are initiated. Further, it implies that if faced by a defensive threat, the PBV designer will work to complete the release of all RVs and the deployment of all decoys and penetration aids in

the shortest possible time once altitude is reached since the PBV represents a high value target until its operation is complete. Alternatively, one could contemplate adding small thrusters to RVs and decoys alike to make up the residual drag caused by the atmosphere, and thus permit release within the atmosphere. The thrust required is independent of the mass of the decoy or the RV provided the decoys have the same shape and size as RVs. Thrust would have to be programmed with altitude for optimum performance, however. It is not clear if this complexity would be an attractive option for the offense.

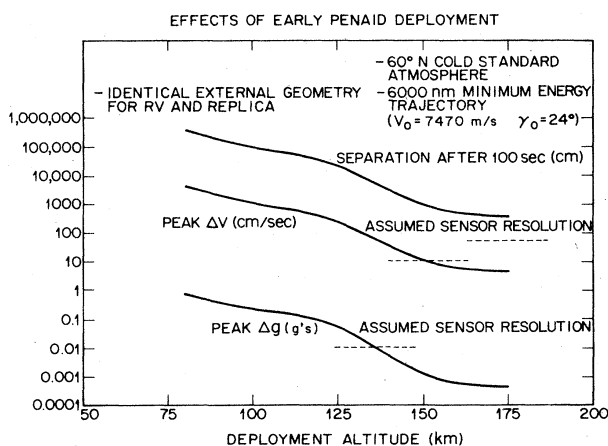
To date there has been no pressure to complete PBV operations rapidly since neither the Soviet Union nor the U.S. has been faced with a defensive threat in the post-boost phase. Only cursory studies have been conducted in the area to date. Nevertheless, a substantial reduction in the time of the PBV phase could be achieved through changes in PBV operations (faster response time controls, improved guidance, software, etc.) while keeping unchanged the basic PBV concept.

An offense, faced with a perceived threat to its missiles in post-boost phase, might also make more drastic changes such as using multiple PBVs (mini-buses) on each booster with each dispensing an RV and one or more decoys against a given target. Such an approach would multiply the number of PBV targets and force the defense to shorter retarget times, shorter kill times, and/or a proliferation of battle stations. Such mini-buses could be released immediately after booster burnout reducing the high leverage enjoyed by post-boost phase defenses. After reaching 120 km altitude, each mini-bus could release its RV and decoys. It is worth noting that the multiple PBV concept will likely become more affordable in the future as electronics, and guidance systems are available at lower weight and volume—trends already present, and believed likely to continue.

In considering the possibilities for rapid deployment from a single PBV or changes to multiple PBV designs it is important to remember that very little work has been done in the area in the U.S. The data needed for the determination of offense/defense cost benefit exchange ratios can only be obtained if more attention (experimental as well as analytical) is given to this important problem.

### 2.3.5 Decoys and Penetration Aids

Once elements of the offense get through a defensive boost and post-boost phase, the battle and thus the offensive response can take on a very different nature. The offense will seek to deploy decoys and other penetration aids in large numbers. The key task in mid-course becomes one of discriminating lightweight decoys from heavy RVs and doing this in a high traffic environment. In thinking about mid-course countermeasures, it is important to remember that there is no atmospheric drag, and so all objects move in ballistic



**Figure 2.9** Atmospheric deceleration as a function of altitude for decoy weighing 1% that of an RV and of identical shape and size. Units of deceleration are g's ( $9.8 \text{ m/g}^2$ ); for other quantities as indicated in parenthesis.

orbits. This permits countermeasures which are extremely lightweight.

We defer most of our discussion of decoys and penetration aids to Chapter 7 (Acquisition, Tracking, and Discrimination). Here we simply note that preliminary designs suggest that effective decoys (i.e., having the same shape and size as a 200 kt RV) can be constructed with a mass of 1–2 kg. Considering that a 200 kt RV might weigh approximately 200 kg, this suggests that for each RV offloaded one might be able to substitute approximately 100 to 200 replica decoys. For example, using the 2 kg figure for the replica mass a single 4000 kg payload booster, therefore, might deliver into the mid-course battle 10 RVs and 1000 decoys (actually from 20 RVs and 0 decoys to 0 RVs and 4000 decoys depending on the offensive missile load-out).

For the nominal case, one sees that if 100 PBVs survive the boost and post-boost phases, the mid-course is faced with 1000 RVs and 100 000 decoys. Or if things go astray for the defense during the first two phase and 1000 PBVs survive, the mid-course defense could be faced with 10 000 RVs and 1 000 000 decoys. The mid-course defense's task is thus *critically* dependent on the success of the defense's boost phase. This cannot be overemphasized.

It is clear that, unless the boost and post-boost defenses are very successful, the mid-course defense faces a massive traffic and discrimination problem.

## 2.4 SUMMARY AND CONCLUSIONS

- One can confidently expect that there will be a strong response from the Soviets to the deployment of any type of missile defense by the U.S.
- Because the precise nature of the Soviet response is unpredictable, the job of designing effective defenses is especially difficult.
- The analysis of responsive threats needs focused analytical and experimental study in order to gain an understanding of the relative technology difficulty, effectiveness, cost, and lead time of defensive and offensive moves.
- It is reasonable that the Soviets will be able to deploy responses even before the U.S. can deploy a DEW defense. Hence U.S. defenses will be pitted against a responsive Soviet threat from the beginning.
- A key problem for boost phase defenses, and even more so for mid-course and terminal defenses, is potentially very high traffic rates. Boost phase is further complicated by potentially very short total battle time. Retarget and kill times are likely to be critical parameters in system architecture choices.
- Preliminary studies suggest that boost phase times can be reduced to less than 60 s. These conclusions need to be explored in detail since such threats would greatly increase the difficulty of building defenses.
- Even after achieving a fast burn booster capability, the offense would still be faced with the need to develop means to deploy RVs and decoys quickly once above the sensible atmosphere. This area needs detailed study to clarify possible limitations and penalties.
- Key issues in the mid-course phase are the potentially very large number of objects with overlapping signatures, the fact that objects in mid-course have small signatures, and the requirement that the defense have large traffic handling capabilities and short, retarget times.
- The combined performance of the boost and post-boost defensive layers is particularly critical since without a reasonably efficient boost/post-boost phase defense, the offense will find proliferation of large boosters an attractive and straightforward response.

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## Chapter 3

# LASERS

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### 3.1 INTRODUCTION AND OVERVIEW

High power lasers are considered potentially attractive as directed energy weapons because of their ability to deliver destructive energy at the speed of light to a distant target. Their promise for high rate of fire as well as agility coupled with aiming could permit tracking of a highly maneuvering target and shifting from target to target on command. The weapons potential of the laser was recognized soon after demonstration of the first lasers in the early sixties, and a broad program of weapons-oriented laser research and development has been conducted by various federal agencies for the last twenty years.

#### 3.1.1 Historical Review

It is possible to gather a historical perspective on the realizability of technology goals from the experience of previous or currently more mature laser device development activities. Three classes of device technologies may be considered for such perspectives: the  $CO_2$  laser,<sup>1</sup> the HF/DF chemical laser,<sup>2</sup> and the Nd-glass solid state laser.<sup>3</sup>

The  $CO_2$  combustion driven gas dynamic laser (GDL) was developed<sup>4</sup> in the latter half of the sixties and a major commitment to build a 1 MW class GDL was made in 1969. This was estimated to be a two-year program. It actually took three years and achieved a substantially reduced level of performance with very poor beam quality. A second generation GDL technology device was built at the several hundred kilowatt level, again with poor beam quality, and a third generation GDL was started in 1974 for the Airborne Laser Laboratory. This device was conceived to be 0.5 MW of power and 1.3 times diffraction limited. Such performance goals were realized, albeit two years later than planned.

In 1976 a commitment was made to develop a HF/DF chemical laser with a near diffraction limited power output in the megawatt class within five years.<sup>5</sup>