Chapter 5

Ballistic Missile Defense Technology: Weapons, Power, Communications, and Space Transportation

CONTENTS

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INTRODUCTION

This chapter reviews weapon technologies relevant to ballistic missile defense (BMD). It emphasizes the chemically propelled hit-to-kill weapons most likely to form the basis of any future U.S BMD deployment in this century. The chapter also covers the directed-energy weapons, power systems, and communication systems of most interest for the Strategic Defense Initiative (SD I). Finally, it considers the new space transportation system essential for a space-based defense.

WEAPONS

A weapon system must transfer a lethal dose of energy from weapon to a target. All existing weapons use some combination of kinetic energy (the energy of motion of a bullet, for example), chemical energy, or nuclear energy to disable the target. The SDI research program is exploring two major new types of weapon systems: directed-energy weapons and ultra-high accuracy and high velocity hit-to-kill weapons. Not only have these weapons never been built before, but no weapon of any type has been based in space. Operating many hundreds or thousands of autonomous weapons platforms in space would itself be a major technical challenge.

Directed-energy weapons (DEW) would kill their prey without a projectile. Energy would travel through space via a laser beam or a stream of atomic or sub-atomic particles. Speed is the main virtue. A laser could attack an object 1,000 km away in 3 thousandths of a second, while a high-speed rifle-bullet, for example, would have to be fired 16 minutes before impact with such a distant target. Clearly, DEW, if they reach the necessary power levels, would revolutionize ballistic missile defense.

DEWS offer the ultimate in delivery speed. But they are not likely to have sufficient deployed power in this century to destroy ballistic missiles, and they certainly could not kill the more durable reentry vehicles (RVs). In hopes of designing a system deployable before the year 2000, the SDI research program has emphasized increased speed and accuracy for the more conventional kinetic-energy weapons (KEW), such as chemically propelled rockets. With speeds in the 4 to 7 km/s range, and with terminal or homing guidance to collide directly with the target, these KEW could kill a significant number of today's ballistic missiles. With sufficient accuracy, they would not require chemical or nuclear explosives.

Although DEWS will not be available for highly effective ballistic missile defense during this century, they could play a significant role in an early 1990s decision on whether to deploy any ballistic missile defense system. That is, the deployment decision could hinge on our ability to persuade the Soviets (and ourselves) that defenses would remain viable for the foreseeable future. Kinetic-energy weapons

Note: Complete definitions of acronyms and initialisms are listed in Appendix B of this report.

work initially against the 1990s Soviet missile threat. But Soviet responsive countermeasures might soon render those weapons ineffective. Thus, a long-term commitment to a ballistic missile defense system would imply strong confidence that new developments, such as evolving DEW or evolving discrimination capability, could overcome and keep ahead of any reasonable Soviet response.

Strategic Defense Initiative Organization (SDIO) officials argue that perceived future capabilities of DEW might deter the Soviet Union from embarking on a costly defense countermeasures building program; instead, the prospect of offensive capabilities might persuade them to join with the United States in reducing offensive ballistic missiles and moving from an offense-dominated to a defense-dominated regime. To foster this dramatic shift in strategic thinking, the evolving defensive system would have to appear less costly and more effective than offensive countermeasures.

Today, the immaturity of DEW technology makes any current judgments of its cost-effectiveness extremely uncertain. It appears that many years of research and development would be necessary before anyone could state with reasonable confidence whether effective DEW systems could be deployed at lower cost than responsive countermeasures. Given the current state of the art in DEW systems, a well-informed decision in the mid-1990s to build and deploy highly effective DEW weapons appears unlikely.[1]

Kinetic-Energy Weapons (KEW)

Today's chemically propelled rockets and sensors could not intercept intercontinental ballistic missiles (ICBMs) or reentry vehicles (RVs) in space. No currently deployable projectile system has the accuracy or speed to consistently intercept an RV traveling at 7 km/s at ranges of hundreds or thousands of kilometers. The SAFEGUARD anti-ballistic missile (ABM) system built near Grand Forks, North Dakota in the early 1970s, and the existing Soviet Galosh ABM system around Moscow both would compensate for the poor accuracy of their radar guidance systems by exploding nuclear warheads. The radiation from that explosion would increase the lethal radius so that the interceptors, despite their poor accuracy, could disable incoming warheads.

The goal of the SDI, however, is primarily to investigate technology for a non-nuclear defense. This would dictate the development of "smart" projectiles that could "see" their targets or receive external guidance signals, changing course during flight to collide with the targets.

The following sections discuss proposed KEW systems, KEW technologies, the current status of technology, and key issues.

KEW Systems

Four different KEW systems were analyzed by SDI system architects, including space-based interceptors (SBIs, formerly called space-based kinetic kill vehicles or SBKKVs), and three ground-based systems. All four systems would rely on chemically propelled rockets.

Space-Based Interceptors (SBIs).–Each system architect proposed-and the SDIO "phase one' proposal includes—deploying some type of space-based projectile. These projectiles would ride on pre-positioned platforms in low-Earth orbits, low enough to reach existing ICBM boosters before their engines would burn out, but high enough to improve the likelihood of surviving and to avoid atmospheric drag over a nominal seven-year satellite life. The range of characteristics for proposed SBI systems is summarized in the classified version of this report.

It would take a few thousand carrier satellites in nearly polar orbits at several hundred

[1] The Study Group of the American Physical Society concluded in their analysis of DEW 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 DEW systems, In addition, the important issues of overall system integration and effectiveness depend critically upon information that, to our knowledge, does not yet exist." See American Physical Society, *Science and Technology of Directed Energy Weapons: Report of the American Physical Society Study Group,* April, 1987, p. 2.

km altitude to attack effectively a high percentage of the mid-1990s Soviet ICBM threat. There was a wide range in the number of interceptor rockets proposed by system architects, depending on the degree of redundancy deemed necessary for functional survivability, on the number of interceptors assigned to shoot down Soviet direct-ascent anti-satellite weapons (ASATs), and on the leakage rates accepted for the boost-phase defense.

In late 1986, the SDIO and its contractors began to examine options for 1990s deployment which would include constellations of only a few hundred carrier vehicles (CVs) and a few thousand SBIs. This evolved into the phase-one design which, if deployed in the mid to late 1990s, could only attack a modest fraction of the existing Soviet ICBMs in their boost and post-boost phases.

Exe-atmospheric Reentry Interceptor System (ERIS).–The ERIS would be a ground-based rocket with the range to attack RVs in the late midcourse phase. Existing, but upgraded, radars such as BMEWS, PAVE PAWS, and the PAR radar north of Grand Forks, North Dakota might supply initial track coordinates to ERIS interceptors.[2] (These radars might be the only sensors available for near-term deployments.) Alternatively, new radars or optical sensors would furnish the track data. Upgraded radars would have little discrimination capability (unless the Soviets were to refrain from using penetration aids); moreover, a single high altitude nuclear explosion could degrade or destroy them.

Optical sensors might reside on a fleet of space surveillance and tracking system (SSTS) satellites or on ground-based, pop-up probes based at higher latitudes. Such sensors might supply early enough infrared (IR) track data

[2]The range of planned ground-based radars such as the Terminal Imaging Radar (TIR), which could discriminate RVs from decoys, might be too short to aid ERIS long-range interceptors; the TIR was planned for the lower HEDI endoatmospheric system. A longer-range Ground-based Radar (GBR) system has also been proposed. This system may be capable of supporting ERIS interceptors.

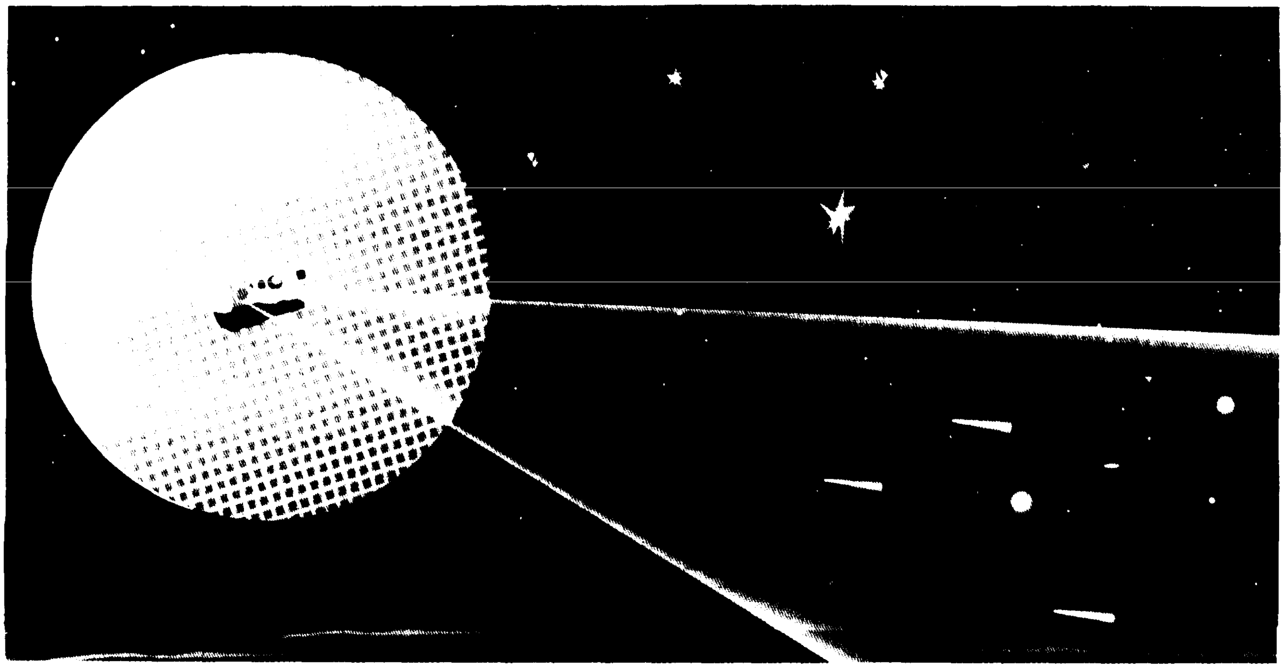


Photo Credit: Lockheed Missiles and Space Company

How ERIS would work.—The ERIS vehicle would be launched from the ground and **its sensors would acquire and track a target at long range, ERIS would then maneuver to intercept the target's path, demolishing it on impact.**

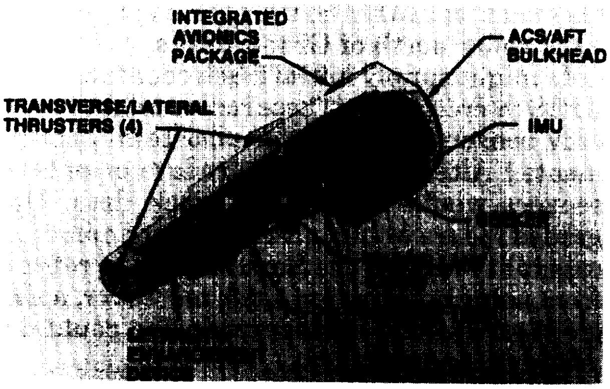


Photo Credit: Lockheed Missiles *and Space Company*

ERIS kill vehicle concept.—The Integrated Avionics Package (IAP) computer (top left) receives interceptor position data from the on-board Inertial Measurement Unit and target position data from the seeker, or infrared sensor. The seeker acquires and tracks the incoming warhead. The IAP sends guidance commands to the two transverse and two lateral thrusters, which maneuver the vehicle to the impact point. Helium is used to pressurize the fuel tanks and also as a propellant for the attitude control system at the aft bulkhead. The lethality enhancement device would deploy just before impact to provide a larger hit area.

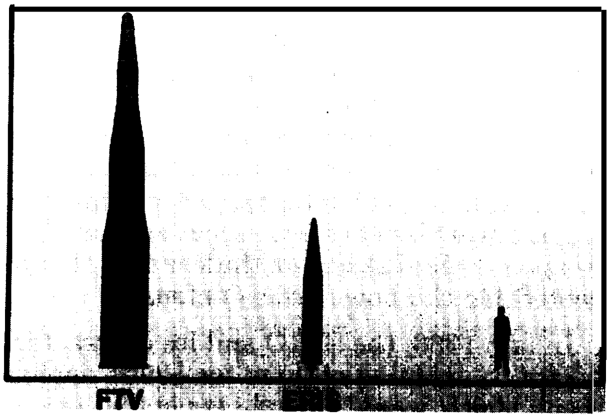


Photo Credit: Lockheed Missiles and Space Company

ERIS Functional Test Validation (FTV) v. baseline ERIS concept.–Sizes of the FTV vehicle and baseline ERIS concepts are compared to a 6-foot-tall man. ERIS is designed as a ground-launched interceptor that would destroy a ballistic missile warhead in space. The FTV vehicle is 33 feet tall, large enough to carry both an observational payload to observe the impact with the warhead and the telemetry to relay information to the ground during the flight tests. The baseline interceptor concept is less than 14 feet tall, more compact because it will not require all the sensors and redundancies that are demanded by flight tests.

to take full advantage of the ERIS fly-out range.[3] If deployed, an airborne optical system (AOS) could give some track data late in mid-course. None of these sensors has been built, although the AirborneOptical Adjunct (AOA), a potential precursor to the AOS airborne system, is under construction and will be test flown in the late 1980s.

Anon-board IR homing sensor would guide the interceptor to a collision with the RV in the last few seconds of flight. This homing sensor would derive from the Homing Overlay Experiment (HOE) sensor, which successfully intercepted a simulated Soviet RV over the Pacific on the fourth attempt, in 1984.

No major improvements in rocket technology would be necessary to deploy an ERIS-like system, but cost would be an important factor. The Army's Strategic Defense Command proposes to reduce the size of the launch vehicle in steps. The Army has proposed—partly to reduce costs–to-test this system with a Functional Technical Validation (FTV) rocket in 1990-91. This missile would have approximately twice the height, 10 times the weight, and twice the burn time of the planned ERIS rocket. The planned ERIS rocket system has a target cost of $1 million to $2 million per intercept in large quantities. Research is proceeding with a view to possible deployment by the mid-1990s.

Much development would be necessary to upgrade the experimental HOE kinetic kill vehicle technology for an operational ERIS interceptor. The IR sensors are being radiation-hardened. Since the operational sensor could not be maintained at the cryogenically low temperatures required for the HOE experiment, higher operating-temperature sensors are being developed, with cool-down to occur after alert or during rocket flight.

High Endo-atmospheric Defense Interceptor (HEDI).–The HEDI system would attack RVs that survived earlier defensive layers of ground-based, high-velocity interceptor

[3] The ERIS, as presently designed, requires a relatively high target position accuracy at hand-off from the sensor. The BSTS would not be adequate for this.

rockets. HEDI would take advantage of the fact that the atmosphere would slow down light-weight decoys more than the heavier RVs. Since it would operate in the atmosphere, HEDI might attack depressed trajectory submarine-launched ballistic missile (SLBM) warheads that would under-fly boost and midcourse defensive layers—provided it received adequate warning and sensor data.

According to one plan, an AOS would track the RVs initially, after warning from the boost-phase surveillance and tracking system (BSTS) and possible designation by SSTS (if available). The AOS would hand target track information off to the ground-based terminal imaging radar (TIR). The TIR would discriminate RVs from decoys both on shape (via doppler imaging) and on their lower deceleration (compared to decoys) upon entering the atmosphere. Interceptors would attack the RVs at altitudes between 12 and 45 km. The HEDI system thus would combine passive optics (IR signature), atmospheric deceleration, and active radar (shape) to distinguish RVs from decoys.

The penalty for waiting to accumulate these data on target characteristics would be the need for a large, high-acceleration missile. The HEDI would have to wait long enough to provide good atmospheric discrimination, but not so long that a salvage-fused RV would detonate a nuclear explosion close to the ground. To accelerate rapidly, the HEDI 2-stage missile must weigh about five to six times more than the ERIS missile.

The key technology challenge for the HEDI system would be its IR homing sensor. This non-nuclear, hit-to-kill vehicle would have to view the RV for the last few seconds of flight to steer a collision course.[4] But very high acceleration up through the atmosphere would severely heat the sensor window. This heated window would then radiate energy back to the IR sensor, obscuring the RV target. In addition, atmospheric turbulence in front of the window could further distort or deflect the RV image. No sensor has been built before to operate in this environment.

The proposed solution is to use a sapphire window bathed with a stream of cold nitrogen gas. A shroud would protect the window until the last few seconds before impact. Since reentry would heat the RV to temperatures above that of the cooled window, detection would be possible. Recent testing gives grounds for optimism in this area.

Fabrication of the sapphire windows (currently 12 by 33 cm) would be a major effort for the optics industry. These windows must be cut from crystal boules, which take many weeks to grow. At current production rates, it would take 20 years to make 1,000 windows. Plans are to increase the manufacturing capability significantly.

The HEDI sensor suite also uses a Nd:YAG[5] laser for range finding. Building a laser ranger to withstand the high acceleration could be challenging.

As with ERIS, plans call for testing a HEDI Functional Technical Validation missile, which is 2 to 3 times larger than the proposed operational vehicle. The proposed specifications of HEDI are found in the classified version of this report.

Flexible Light-Weight Agile Experiment (FLAGE).–The weapon system expected to evolve from FLAGE research would be the last line of defense, intercepting any RVs which leaked through all the other layers. Its primary mission would be the defense of military targets against short range missiles in a theater war such as in Europe or the Middle East. The FLAGE type of missile would intercept RVs at altitudes up to 15 km. The homing sensor for FLAGE would use an active radar instead of the passive IR sensor proposed for on all other KEW homing projectiles.

[4]The HEDI interceptor would probably include an explosively driven "lethality enhancer."

[5]"Nd:YAG" is the designation for a common laser used in research and for military laser range-finders. The "Nd" represents neodymium, the rare element that creates the lasing action, and "YAG" stands for yttrium-aluminum-garnet, the glass-like host material that carries the neodymium atoms.

The FLAGE system was flown six times at the White Sands Missile Range. On June 27, 1986, the FLAGE missile successfully collided with an RV-shaped target drone which was flown into a heavily instrumented flight space. The collision was very close to the planned impact point. Another FLAGE interceptor collided with a Lance missile on May 21, 1987.

The FLAGE program ended in mid-1987 with the Lance intercept. A more ambitious Extended Range Intercept Technology (ERINT) program succeeds it. The ERINT interceptors will have longer range and "a lethality enhancer. " FLAGE was a fire-and-forget missile; no information was transmitted from any external sensor to the missile once it was fired. The ERINT missiles are to receive mid-course guidance from ground-based radars. Six test launches are planned at the White Sands Missile Range.

KEW Technology

Three types of KEW propulsion have been proposed for SDI: conventional projectiles powered by chemical energy, faster but less well-developed electromagnetic or "railgun" technology, and nuclear-pumped pellets. All system architects nominated the more mature chemically propelled rockets for near-term BMD deployments.

How Chemical Energy KEWs Work.–There are three different modes of operation proposed for chemically propelled KEWs:

- space-based rockets attacking boosters, post-boost vehicles (PBVs), RVs, and direct-ascent ASATs;
- ground-based rockets attacking RVs in late mid-course outside the atmosphere, and
- ground-based rockets attacking RVs inside the atmosphere.

Two or more rocket stages would accelerate the projectile toward the target. The projectile would be the heart of each system and would entail the most development.

The smart projectile for the space-based mission would need some remarkable features. It would be fired at a point in space up to hundreds of seconds before the actual interception.[6] After separation from the last rocket stage, the projectile would have to establish the correct attitude in space to "see" the target: in general the line-of-sight to the target would not correspond with the projectile flight path. If it had a boresighted sensor that stared straight ahead, then the projectile would have to fly in an attitude at an angle to its flight path to view the target (see figure 5-1).[7]

The projectile would have to receive and execute steering instructions via a secure communications channel from the battle manager. Usually just a few seconds before impact, the projectile would need to acquire the target–either a bright, burning booster or a much dimmer PBV—with an on-board sensor. It would then make final path corrections to effect a collision. Fractions of a second before impact, it might deploy a "lethality enhancement device' –like the spider-web structure used in the Army's Homing Overlay Experiment (HOE)–to increase the size of the projectile and therefore its chance of hitting the target.

The SBI projectile must have these components:

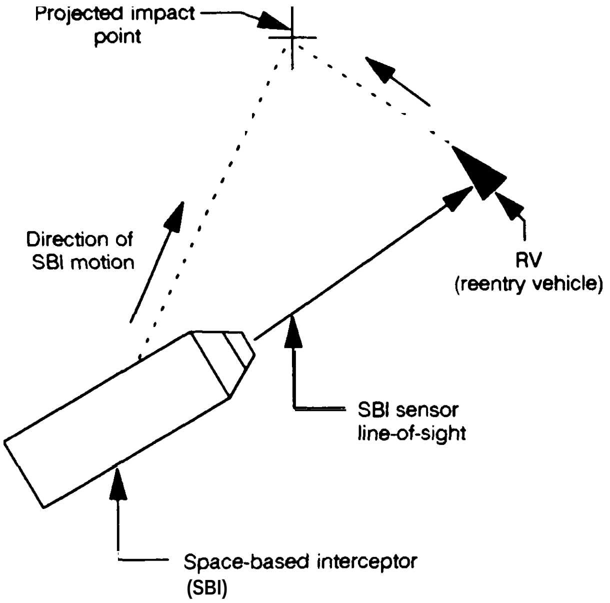
- an inertial guidance system,
- a secure communications system,
- a divert propulsion system,
- an attitude control system,
- a sensor for terminal homing (including vibration isolation),
- a lethality enhancement device (optional?), and
- a computer able to translate signals from the sensor into firing commands to the divert propulsion system in fractions of a second.

The on-board sensors envisaged by most system architects for more advanced "phase-two"

[6] A computer in the battle management system would estimate the actual interception aim-point in space by projecting the motion or track of the target using the sensor track files.

[7] For non-accelerating targets, this look angle would not change, even though the target and the projectile were traveling at different velocities. In this "proportional navigation" mode, the projectile orientation would be fixed once the sensor was aimed at the target.

Figure 5.1.—Orientation of SDI to RV



Orientation of the space-based interceptor (SBI) to the reentry vehicle (RV) during the homing phase of the flight. (This drawing shows a sensor bore-sighted with the axis of the SBI, which is common for guided missiles operating in the atmosphere. For space-based interceptors, the sensor could just as well look out the side of the cylindrical projectile.) The SBI sensor would have to be aimed at the RV so that its line-of-sight would not be parallel to the SBI flight path (except for a head-on collision.) For a non-accelerating RV, the angle from the sensor line-of-sight to the SBI flight path would be fixed throughout the flight. Since targets such as ICBM boosters and post-boost vehicles do change acceleration during flight, then this look angle and hence the orientation of the SBI would have to be changed during the SBI flight.

SOURCE Office of Technology Assessment, 1988,

space-based interceptors may be particularly challenging because they would perform several functions. They would track not only the ICBM during the boost phase, but also the PBV, RVs, and direct-ascent ASAT weapons sent up to destroy the BMD platforms. Each SBI would, ideally, kill all four types of targets.

In the boost phase, a short-wave infrared (SWIR) or medium-wave infrared (MWIR) sensor with existing or reasonably extended technology could track a hot missile plume. An SBI would still have to hit the relatively cool missile body rather than the hot exhaust plume. Three approaches have been suggested for detecting the cooler missile body: computer algorithm, separate long-wave infrared (LWIR) sensor, or laser designation.

A computer algorithm would steer the SBI ahead of the plume centroid by a prescribed distance that would depend on the look angle of the SBI relative to the booster and on the booster type. Predicting the separation between the plume centroid and the booster body under all conditions might be difficult or even impractical if that separation varied from one booster to the next.

A separate LWIR sensor channel might acquire and track the cold booster body.[8] One designer proposed a single detector array, sensitive across the IR band, in combination with a spectral filter. This filter would move mechanically to convert the sensor from MWIR to LWIR capability at the appropriate time. Finally, in some designs a separate laser on the weapon platform or on an SSTS sensor would illuminate the booster. In this case a narrow-band filter on the interceptor's sensor would reject plume radiation, allowing the SBI to home in on laser light reflected from the booster body.

In the post-boost and mid-course phases of the attack, the SBI would have to track hot or warm PBVs and cold RVs. Therefore either SBIs would need to have much more sophisticated LWIR sensors, or they would need something like laser designators to enhance the target signature. This laser illumination need not be continuous, except possibly during the last few seconds before impact. But intermittent illumination would place another burden on the battle manager: it would have to keep track of all SBIs in flight and all SBI targets, then instruct the laser designator at the right time to illuminate the right target.

An SBI lethality enhancer might, for example, consist of a spring-loaded web which ex-

'There is also a possibility that an SWIR or MWI R sensor could acquire a cold booster body. At 4.3 μm, for example, the atmosphere is opaque due to CO_2 absorption, and the upper atmosphere at a temperature of 2200 K would be colder than a booster tank at 3000 K. As an SBI approached a booster, the latter would appear to a 4.3 μm sensor as a large, warm target against the background of the cool upper atmosphere, panded to a few meters in diameter or an explosively propelled load of pellets driven radially outward. Weight would limit the practical diameter of expansion. System designers would have to trade off the costs of increased homing accuracy with the weight penalty of increased lethality diameter.

Ground-based KEW capabilities would resemble those of space-based interceptors. Exoatmospheric projectiles that intercept the RVs outside the Earth's atmosphere would use LWIR homing sensors to track cold RVs, or they would employ other optical sensors to track laser-illuminated targets. These interceptors would be command-guided to the vicinity of the collision by some combination of ground-based radars, airborne LWIR sensors (AOS) or space-borne LWIR sensors (SSTS, BSTS, or rocket-borne probes). Long-wave infrared homing sensors in the projectile would have to be protected during launch through the atmosphere to prevent damage or overheating.

Current Status of Chemically Propelled Rockets.–No interceptor rockets with BMD-level performance have ever been fired from space-based platforms. Operational IR heat-seeking interceptor missiles such as the air-to-air Sidewinder and the air-to-ground Maverick are fired from aircraft, but both the range and the final velocity of this class of missiles are well below BMD levels.

The SDIO's Delta 180 flight test included the collision of two stages from a Delta rocket after the primary task of collecting missile plume data was completed. However, these two stages were not interceptor rockets, were not fired from an orbiting platform, did not have the range nor velocity necessary for BMD, and were highly cooperative, with the target vehicle orienting a four-foot reflector toward the homing vehicle to enhance the signal for the radar homing system. Note that this test used radar homing, whereas all SBI designs call for IR homing or laser-designator homing. This experiment did test the tracking algorithms for an accelerating target, although the target acceleration for this nearly head-on collision was not as stressing as it would be for expected BMD/SBI flight trajectories.[9]

Engineers have achieved very good progress in reducing the size and weight of components for the proposed space-based interceptors. They have developed individual ring laser gyroscopes weighing only 85 g as part of an inertial measuring unit. They have reduced the weight of divert propulsion engines about 9 kg to 1.3 kg. Gas pressure regulators to control these motors have been reduced from 1.4 kg to .09 kg each. The smaller attitude control engines and valves have been reduced from 800 g each to 100 g each. Progress has also been made on all other components of a SBI system, although these components have not as yet been integrated into a working prototype SBI system.

Ground-based interceptor rockets are one of the best developed BMD technologies. The Spartan and Sprint interceptor missiles were operational for a few months in the mid 1970s. Indeed parts of these missiles have been recommissioned for upcoming tests of SDI ground-based weapons such as the endo-atmospheric HEDI. The production costs for these missiles would have to be reduced substantially to make their use in large strategic defense systems affordable, but no major improvements in rocket technology are needed for ground-based interceptors, other than a 30 percent improvement in speed for the HEDI missile. As discussed in chapter 4, however, major sensor development would be necessary for these interceptors.

Key Issues for Chemical Rockets.–Chemical rocket development faces four key issues, all related to space-based deployment and all derived from the requirement to design and make very fast SBIs.

Constellation Mass. —The overriding issue for SBIs is mass. The SBIs must be so fast

'Previous tests of IR guided projectiles such as the Homing Overlay Experiment against a simulated RV and the F-16 launched ASAT test against a satellite, shot down non-accelerating targets.

that a reasonably small number of battle stations could cover the entire Earth. But, for a given payload, faster rockets consume much more fuel-the fuel mass increases roughly exponentially with the desired velocity. The designer must compromise between many battle stations with light rockets or fewer battle stations with heavier rockets.[10]

These trade-offs are illustrated in figure 5-2, which assumes a boost-phase-only defense with three hypothetical rocket designs: a state-of-the-art rocket based on current technology; a "realistic" design based on improvements in rocket technology that seem plausible by the mid-1990s; and an "optimistic" design that assumes major improvements in all areas of rocket development. The key parameters assumed for SBI rocket technology appear in the classified version of this report. In all cases analyzed, OTA assumed the rockets to be "ideal": the mass ratio of each stage is the same, which produces the lightest possible rocket.[11] The first chart in figure 5-2a shows that rocket mass increases exponentially with increasing velocity, limiting practical SBI velocities to the 5 to 8 km/s range for rockets weighing on the order of 100 kg or less.

For analytic purposes, OTA has considered constellations of SBIs that would be necessary to intercept virtually 100 percent of postulated numbers of ICBMs. *It should be noted that since the system architecture analyses of 1986, SDIO has not seriously considered deploying SBIs that would attempt to intercept anywhere near 100 percent of Soviet ICBMs and PBVs.*[12] This OTA analysis is intended only to give a feel for the parameters and trade-offs involved in a system with SBIs.

Deployment of a system of "state-of-the-art" SBIs intended to provide 100 percent coverage of Soviet ICBMs would entail 11.7 million kg of CVs; waiting for the development of the "realistic" SBI would reduce the mass to orbit by a factor of two.

Figure 5-2b shows the number of SBI carrier platforms and figure 5-2c shows the number of SBIs for a 100 percent-boost-phase defense as a function of SBI velocity. The last chart (figure 5-2d) shows the total constellation mass as a function of velocity. The number of CVs was calculated initially to optimize coverage of existing Soviet missile fields: the orbits of the CVs were inclined so that the CVs passed to the north of the missile fields by a distance equal to the SBI fly-out range.[13] Each CV therefore stayed within range of the ICBM fields for a maximum period during each orbit.

The "optimal" number of CVs resulting from this calculation was so low as to endanger system survivability (see ch. 11), calling for up to 100 SBIs per carrier to cover the existing Soviet ICBM threat: such concentrations would provide lucrative targets for the offense's ASATs. To increase survivability, the number of CVs was therefore increased by a factor of 3 for the data in figure 5-2. Some polar orbits were added to cover the SLBM threat from northern waters.

The number of SBIs was calculated initially to provide one SBI within range of each of 1,400 Soviet ICBMs sometime during the boost phase. The booster burn time was taken as similar to that of existing Soviet missiles, with a reasonable interval allotted for cloud-break, initial acquisition, tracking, and weapons launch.

One SBI per booster would not do for a robust (approaching 100 percent coverage) boost-phase defense. A substantial number of SBIs

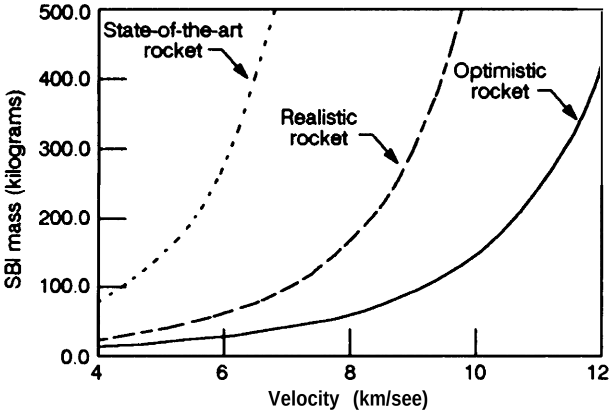
'"Projectile mass might not be as critical for ground-based as for space-based KEW projectiles, since there would be no space transportation cost. However, the projectile mass should still be minimized to reduce the over-all rocket size and cost, and to permit higher accelerations and final velocities.

[11]The mass fraction for a rocket stage is defined as the ratio of the propellant mass to the total stage mass (propellant plus rocket structure). The mass fraction does not include the payload mass. For the calculations reported here, an ideal rocket is assumed: it has equal mass ratios for each stage, where mass ratio is defined as the initial stage weight divided by the stage weight after burn-out (both including the payload; it can be shown that the rocket mass is minimized for a given burnout velocity if each stage has the same mass ratio.)

[12]As indicated in chapters 1,2, and 3, SDIO argues that the deterrent utility of defenses far more modest than those needed for "assured survival" would make them worthwhile.

*The locations of Soviet missile fields are estimated from maps appearing in U.S. Department of Defense, *Soviet Military Power, 1987* (Washington, D. C.: Department of Defense, 1987), p. 23. See adaptation of this map in chapter 2 of this OTA report.

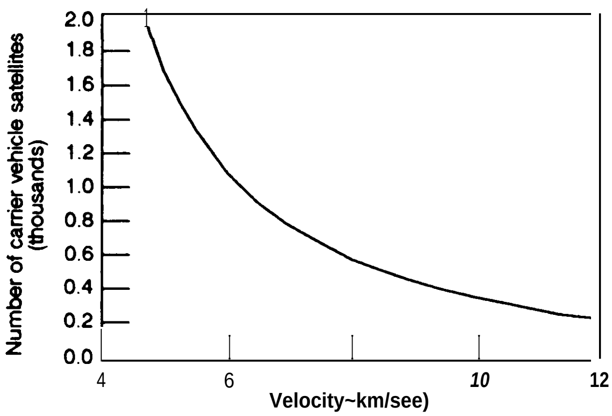
Figure 5-2a. -Space-based Interceptor Mass v. Velocity



The SBI mass versus SBI velocity. These data assume 100°/0 coverage of the current Soviet threat of 1,400 ICBMs. It should be noted that the SDIO currently proposes a substantially lower level of coverage for SBIs. Therefore, the absolute numbers in the OTA calculations are not congruent with SDIO plans. Rather, the graphs provided here are intended to show the relationships among the various factors considered. It should also be noted that numerous assumptions underlying the OTA analyses are unstated in this unclassified report, but are available in the classified version.

SOURCE: Office of Technology Assessment, 1988.

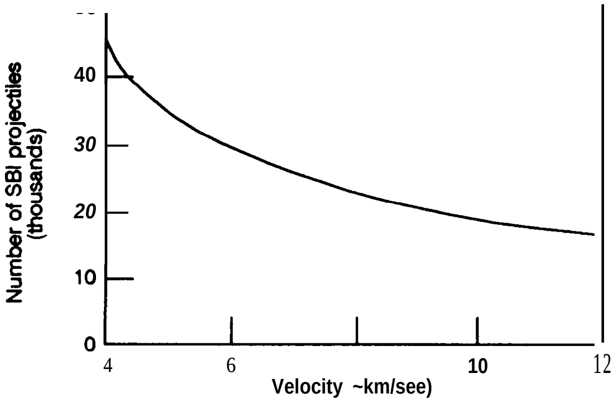
Figure 5-2b.-Number of Satellites v. SBI Velocity



The number of SBI carrier satellites v. SBI velocity.

SOURCE: Office of Technology Assessment, 1988

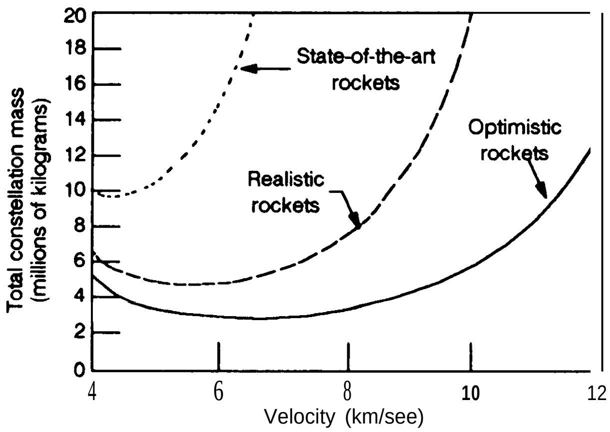
Figure 5-2c. -Number of Space-Based Interceptors v. Velocity (Inclined orbits + SLBM polar orbits)



The number of space-based interceptors (SBIs) required to provide one SBI within range of each of 1,400 existing Soviet ICBMs before booster burnout. '

SOURCE: Office of Technology Assessment, 1988.

Figure 5-2d. -Constellation Mass v. SBI Velocity



The total constellation mass in orbit (SBIs and carrier vehicles, excluding sensor satellites) v. SBI velocity. The minimum constellation mass for the "realistic" SBI to be in position to attack all Soviet boosters would be about 5.3 million kg. Faster SBIs would permit fewer carrier vehicles and fewer SBIs, but the extra propellant on faster SBIs would result in a heavier constellation. For reference, the Space Shuttle can lift about 14,000 kg into polar orbit, a 5.3 million kg constellation would require about 380 Shuttle launches, or about 130 launches of the proposed "Advanced Launch System" (ALS), assuming it could lift 40,000 kg into near-polar orbit at suitable altitudes.

SOURCE: Office of Technology Assessment, 1988.

would fail over the years just due to electronic and other component failures. The number of SBIs in figure 5-2 was increased by a plausible factor to account for this natural peacetime attrition. In addition, during battle, some SBIs would miss their targets, and presumably Soviet defense suppression attacks would eliminate other CVs and draw off other SBIs for self-defense.

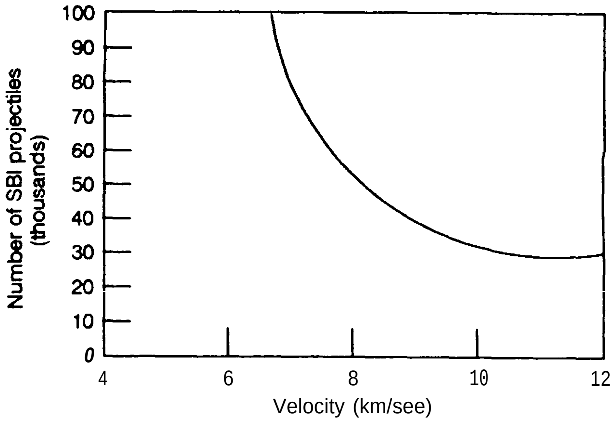
Given the above assumptions, figure 5-2 represents the SBI constellation for nearly 100 percent coverage of the existing Soviet ICBM fleet in the boost phase, with modest survivability initially provided by substantial SBI redundancy, degrading to no redundant SBIs as "natural" attrition set in.

Note that for each type of rocket there is an optimum velocity that minimizes the total mass that would have to be launched into space; lower velocity increases the number of satellites and SBIs, while higher velocity increases the fuel mass. In OTA's analysis, the minimum mass which would have to be launched into orbit for the "realistic" rocket is *5.3* million kg (or 11.7 million lb); the mass for a constellation of "optimistic" SBIs would be 3.4 million kg.

The data for figure 5-2 all assume booster burn times similar to those of current Soviet liquid-fueled boosters. Faster-burning rockets would reduce the effective range of SBIs and would therefore increase the needed number of carrier satellites. The same SBI parameters are shown in figures 5-3a and b with an assumption of ICBM booster burn time toward the low end of current times. The minimum constellation mass has increased to 29 million and 16 million kg, respectively, for the "realistic" and "optimistic" rocket designs.

Several studies of "fast-burn boosters" concluded that reducing burn-time would impose a mass penalty, so the Soviets would have to off-load RVs (or decoys) to reduce burn time significantly. But these same studies showed that there is no significant mass penalty for burn times as low as 120 s. About 10-20 percent of the payload would have to be off-loaded for burn times in the 70 to 90 s range.

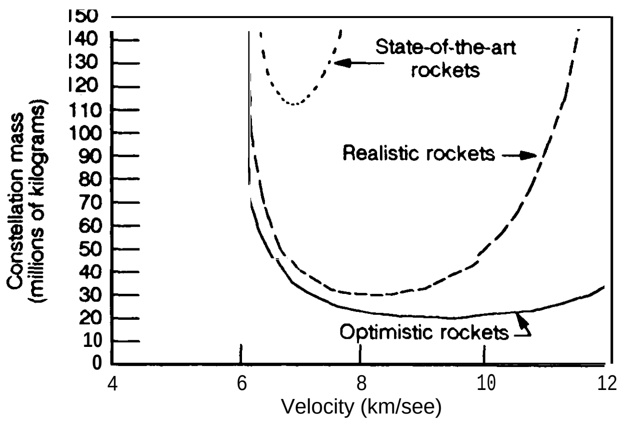
Figure 5-3a. -Number of Projectiles v. SBI Velocity
(160 second burn-time)



The number of space-based interceptors v. SBI velocity for reduced booster burntime (within currently applied technology).

SOURCE: Office of Technology Assessment, 1988.

Figure 5-3b. -SBI Constellation Mass v. SBI Velocity
(160 second burn-time)

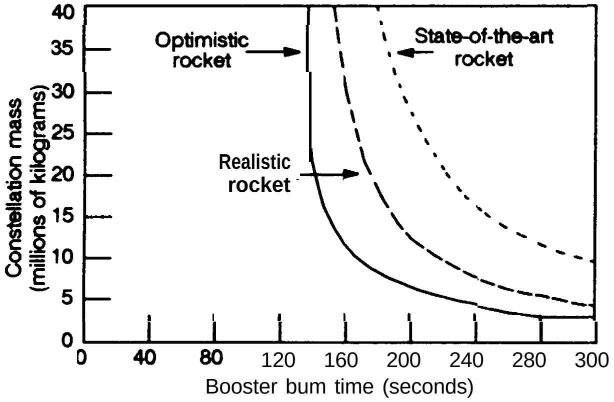


The total constellation mass (carrier vehicles and SBIs) versus SBI velocity for reduced booster burn times, assuming one SBI within range of each of 1,400 boosters before burnout.

SOURCE: Office of Technology Assessment, 1988

If the Soviet Union could reduce the burn time of its missiles below that of any currently deployed ICBMs, then the total SBI constellation mass necessary for boost-phase intercept would increase dramatically. The minimum constellation mass to place one SBI within range of each ICBM during its boost phase is shown in figure 5-4 as a function of

Figure 5-4.-Total SBI Constellation Mass in Orbit v. Booster Burn Time



The effect of Soviet booster burn time on SBI constellation mass. If we consider 40 million kg as a maximum conceivable upper bound on constellation mass (corresponding to 2,800 Shuttle flights or 1,000 launches of the proposed ALS system), then booster times of 120 to 150 seconds would severely degrade a 100%-boost-phase defense with chemically propelled rockets. The ability of smaller constellations of SBIs to achieve lesser goals would be analogously degraded by the faster burn times.

All assumptions are the same as for the previous figures, except for the burn-out altitude, which varies with burn-time.

SOURCE: Office of Technology Assessment, 1988.

booster burn time for the three canonical rocket designs.

The masses described above for a boost-phase-only defense are clearly excessive, particularly for a responsive Soviet threat. Adding other defensive layers would reduce the burden on boost-phase defense. The next layer of defense would attack PBVs, preferably early in their flight before they could unload any RVs.

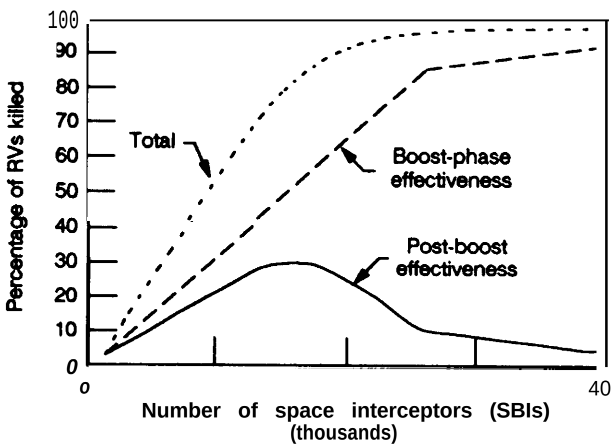
A PBV or "bus" carrying up to 10 or more RVs would be more difficult to track and hit than a missile. A PBV has propulsion engines that emit some IR energy, but this energy will be about 1,000 times weaker than that from a rocket plume.[14] A PBV is also smaller and less fragile than a booster tank. In short, a PBV is harder to detect and hit with an SBI. However, a PBV is still bigger and brighter than an RV; sensors might acquire the PBV if its initial trajectory (before its first maneuver) can be estimated by projecting the booster track.

The effectiveness of a combined boost and post-boost defense in terms of the percentage of RVs killed is estimated in figure 5-5 for the "realistic" SBI rocket. The calculation assumes that 1,400 missiles resembling today's large, heavy ICBMs are spread over the existing Soviet missile fields.

The net effect of attacking PBVs is to reduce the number of SBIs needed to kill a given number of RVs. For example, to destroy 85 percent of the Soviet RVs carried by ICBMs, a boost-only defense system would require about 26,000 SBIs in orbit. Adding PBV interceptions reduces the number of SBIs needed to about 17,000.

A defensive system must meet the expected Soviet threat at the actual time of deployment, not today's threat. For example, the Soviet Union has already tested the mobile, solid-fueled SS-24 missile, which can carry 10 war-

Figure 5-5.—Boost and Post-Boost Kill Effectiveness (1,400 ICBMs v. "Realistic" SBIs)



Percentage of reentry vehicles (RVs) killed as a function of the number of space-based interceptors (SBIs) deployed in space. This calculation assumes a threat of 1,400 ICBMs spread over the Soviet missile fields. The SBIs have a plausible single-shot probability of killing a booster and a slightly smaller chance of killing a PBV; a substantial fraction of the SBIs are used for self-defense (or are not functional at the time of attack).

SOURCE: Office of Technology Assessment, 1988,

[14]The first stage of an ICBM might radiate 1 million W/sr, the second stage 100,000 W/sr, while a PBV may emit only 100 W/sr. On the other hand, the RV radiates only 5 W/sr, so the PBV is a better target than an RV.

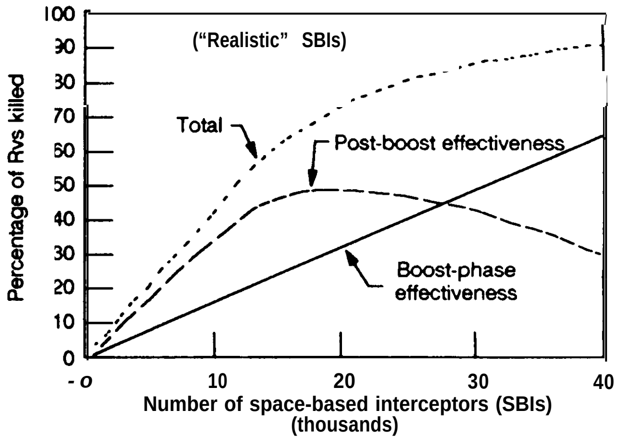
heads. There is no reason to doubt that the Soviets could deploy this kind of missile in quantity by the mid-1990s. Such a fleet would particularly stress a space-based defense if deployed at one or a few sites, since more SBIs would be needed in the area of deployment concentration.

The effects on the combined boost and post-boost defense of clustering 500 shorter-burn-time, multiple-warhead missiles at three existing SS-18 sites are shown in figure 5-6a. It would take about 23,000 SBIs to stop 85 percent of these 5,000 warheads. If the assumed 500 ICBMs were concentrated at one site (but still with 10 km separation to prevent "pin-down" by nuclear bursts), then 30,000 SBIs would be needed (see fig. 5-6b).[15]

Finally, the Soviets might deploy 200 (or more) current-technology, single-warhead missiles atone site, as shown in figure 5-7. In this case, no reasonable number of SBIs could intercept 85 percent of these 200 extra warheads (50,000 SBIs in orbit would kill 70 percent). Twice as many RVs are destroyed in the post-boost period as the boost-phase. Once this concentrated deployment was in place, the defense would have to add about 185 extra SBIs and their associated CVs to achieve a 50 percent probability of destroying each new ICBM deployed.

SBI Projectile Mass.—The constellation masses shown above assume that the mass of the smart SBI projectile (including lateral divert propulsion, fuel, guidance, sensor, communications, and any lethality enhancer) can be reduced to optimistic levels. Current technology for the various components would result in an SBI with a relatively high mass. Thus mass reduction is essential to achieve the results outlined above; total constellation mass would scale almost directly with the achievable SBI mass.

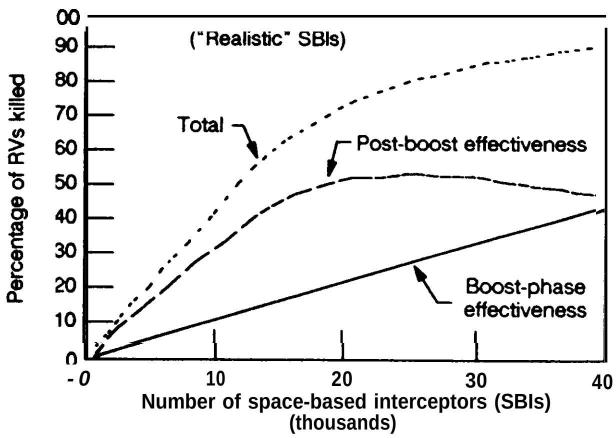
Figure 5-6a.— Boost and Post-Boost Kill Effectiveness (500 single.RV ICBMs at three sites)



The percentage of RVs from modestly short-burn ICBMs killed as a function of the number of SBIs deployed in space. This curve corresponds to 500 such ICBMs deployed at 3 existing SS-18 sites. All SBI parameters are the same as in previous figures.

SOURCE: Office of Technology Assessment, 1988

Figure 5-6b.—Boost and Post-Boost Kill Effectiveness (500 single.RIV ICBMs at one site)



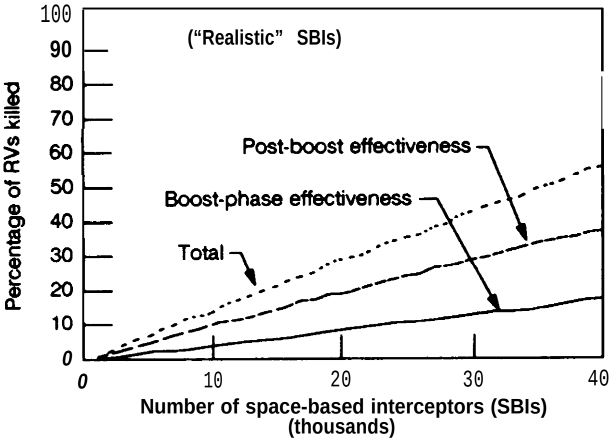
This curve assumes that all 500 shorter-burn ICBMs are deployed at one site (but still with 10 km separation to prevent pin-down). All other parameters are the same as figure 5-6a.

SOURCE: Office of Technology Assessment, 1988,

Rocket Specific Impulse. —Similarly, the specific impulse of the rocket propellant would have to be improved from current levels. The specific impulse, expressed in seconds, measures the ability of a rocket propellant to change mass into thrust. It is defined as the ratio of thrust (lb) divided by fuel flow rate (lb/s).

"Concentrating 500 missiles atone site would have disadvantages for an offensive attack: timing would be complicated to achieve simultaneous attacks on widely separated U.S. targets, and Soviet planners may be reluctant to place so many of their offensive forces in one area, even if the missiles are separated enough to prevent one U.S. nuclear explosion from destroying more than one Soviet missile.

Figure 5-7. - Boost and Peat-Boost Kill Effectiveness
(200 "medium-burn-booster" ICBMs at one site)



Percentage of single-warhead ICBM RVs killed as a function of number of SBIs in space. The 200 single-warhead ICBMs are deployed at one site with 10 km separation. All SBI parameters are as in previous figures.

SOURCE: Office of Technology Assessment, 1988.

The specific impulse of current propellants varies from 240 to 270 s for solid fuel and up to 390s at sea level for liquid oxygen and liquid hydrogen fuel. Assuming that BMD weapons would utilize solid fuels for stability and reliability, then the specific impulse for current technology would be limited to the 270-s range.[16] One common solid propellant, hydroxyl-terminated polybutadiene (HTPB) loaded with aluminum, has an impulse in the 260-to-265-s range. This can be increased to 280s by substituting beryllium for the aluminum. Manufacturers of solid propellant say that further improvements are possible.

Rocket Mass Fraction.—Finally, the mass fraction-the ratio of the fuel mass to the stage total mass (fuel plus structure but excluding payload) –would have to be raised to meet SDI objectives. Large mass fractions can be achieved for very big rockets having 95 percent of their mass in fuel. It would be more difficult to reduce the percentage mass of structure and propulsion motor components for very small SBI rockets.

The mass fraction can be increased by reducing the mass of the rocket shell. New lighteight, strong materials such as carbon graphite fiber reinforced composite materials or judicious use of titanium (for strength) and aluminum (for minimum mass) may permit increased mass fractions for future rockets.

How Electromagnetic Launchers (EML) Work. –Electromagnetic launchers or "railguns" use electromagnetic forces instead of direct chemical energy to accelerate projectiles along a pair of rails to very high velocities. The goal is to reach higher projectile velocities than practical rockets can. This would extend the range of KEW, expanding their ability to attack faster-burn boosters before burn-out. Whereas advanced chemically propelled rockets of reasonable mass (say, less than 300 kg) could accelerate projectiles to at most 9 to 10 km/s, future EML launchers might accelerate small projectiles (1 to 2 kg) up to 15 to 25 km/s. SDIO has set a goal of reaching about 15 km/s.

In principle, chemical rockets could reach these velocities simply by adding more propellant. The efficiency of converting fuel energy into kinetic energy of the moving projectile decreases with increasing velocity, however: the rocket must accelerate extra fuel mass that is later burned. A projectile on an ideal, staged rocket could be accelerated to 15 km/s, but only 17 percent of the fuel energy would be converted into kinetic energy of the projectile, down from 26 percent efficiency for a 12 km/s projectile. Since a railgun accelerates only the projectile, it could theoretically have higher energy efficiency, which would translate into less mass needed in orbit.

In practice, however, a railgun system would not likely weigh less than its chemical rocket counterpart at velocities below about 12 km/s, since railgun system efficiency would probably be on the order of 25 percent at this velocity.[17]

[16] The SBI divert propulsion system in the final projectile stage would probably use liquid fuel, and some have suggested that the second stage also use liquid fuel.

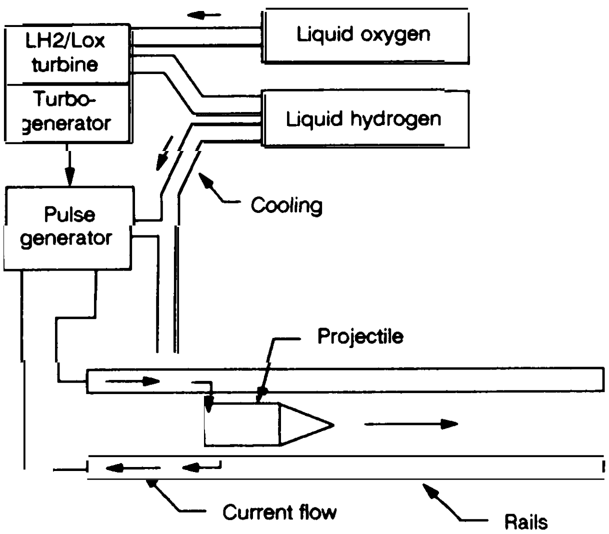
[17] This assumes 50 percent efficiency for converting fuel (thermal) energy into electricity, 90 percent efficiency in the pulse forming network, and 55 percent rail efficiency in converting electrical pulses into projectile kinetic energy. The SDIO has a goal of reaching 40 percent overall EML system efficiency, but this would require the development of very high temperature (2,000 to 2,500° K) nuclear reactor driven turbines. The total system mass might still exceed that of a comparable chemical rocket system.

Therefore a railgun system would have to carry as much or more fuel than its chemical rocket equivalent-in addition to a massive rocket-engine generator system, an electrical pulse-forming network to produce the proper electrical current pulses, and the rail itself.

The conventional "railgun" (see figure 5-8) contains a moving projectile constrained by two conducting but electrically insulated rails. A large energy source drives electrical current down one rail, through the back end of the moving projectile, and back through the other rail. This closed circuit of current forms a strong magnetic field, and this field reacts with the current flowing through the projectile to produce a constant outward force. The projectile therefore experiences constant acceleration as it passes down the rail.

The final velocity of the projectile is proportional to the current in the rail and the square root of the rail length; it is inversely proportional to the square root of the projectile mass. High velocity calls for very high currents (millions of amperes), long rails (hundreds of m), and very light projectiles (1 to *2* kg).

Figure 5-8.-Schematic of an Electromagnetic Launcher (EML) or "Railgun"



Schematic of an electromagnetic launcher (EML) or "Railgun. " In operation, a strong pulse of electrical current forms a circuit with the conducting rails and the projectile. This current loop generates a magnetic field. The interaction of this field with the current passing through **the moving projectile produces a constant outward force on the projectile, accelerating it to high velocities.**

SOURCE' Office of Technology Assessment, 1988.

For the BMD mission, the projectile must be "smart". That is, it must have all of the components of the chemically propelled SBIs: a sensor, inertial guidance, communications, divert propulsion, a computer, and possibly a lethality enhancement device. The EML projectile must be lighter, and it must withstand accelerations hundreds of thousands times greater than gravity, compared to 10 to 20 "g's" for chemically propelled SBIs.

Researchers at Sandia National Laboratory have proposed another type of EML launcher which would employ a series of coils to propel the projectile. Their "reconnection gun" would avoid passing a large current through the projectile, eliminating the "arcs and sparks" of the conventional railgun. The term "reconnection" derives from the action of the moving projectile: it interrupts the magnetic fields of adjacent coils, and then these fields "reconnect" behind the projectile, accelerating it in the process.

Current Status of EMLs.—Several commercial and government laboratories have built and tested experimental railguns over the last few decades. These railguns have fired very small plastic projectiles weighing from 1 to *2,500 g,* accelerating them to speeds from 2 to 11 km/s. In general, only the very light projectiles reached the 10 km/s speeds.

One "figure of merit," or index, for railgun performance is the kinetic energy supplied to the projectile. For BMD applications, SDIO originally set a goal of a 4 kg projectile accelerated to 25 km/s, which would have acquired 1,250 MJ of energy. SDIO officials now state that their goal is a 1 kg projectile at 15 km/s, which would acquire 113 MJ of kinetic energy. The highest kinetic energy achieved to date was 2.8 MJ (317 g accelerated to 4.2 km/s), or about 50 to 400 times less than BMD levels.

Finally, there have been no experiments with actual "smart" projectiles. All projectiles have been inert plastic solids. Some (non-operating)

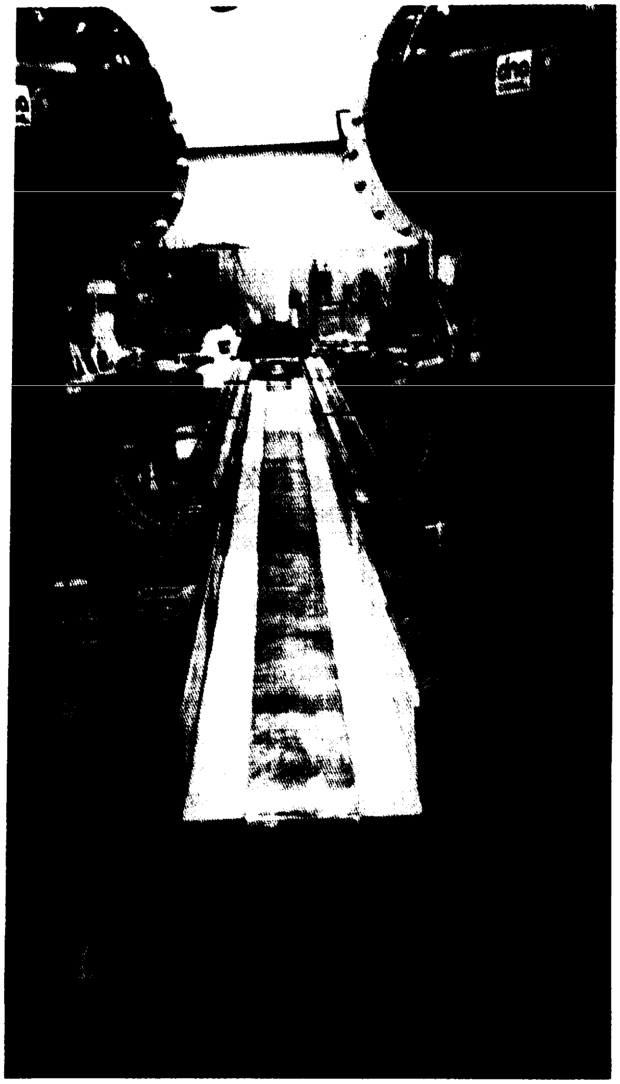


Photo credit: Contractor photo released by the U.S. Department of Defense

Electromagnetic launcher.—This experimental electromagnetic launcher at Maxwell Laboratories, Inc., San Diego, CA, became operational late in 1985.

electronic components, including focal plane arrays, have been carried on these plastic bullets to check for mechanical damage. Results have been encouraging.

Key Issues for EMLs.—Much more research must precede an estimate of the potential of EML technology for any BMD application. The key issues are summarized in table 5-1. There is uncertainty at this time whether all these issues can be favorably resolved.

Table 5-1 .—Key Issues for Electromagnetic Launchers (EML)

- **Low-mass (2 kg or less), high acceleration (several hundred thousand g) projectile development.**
- **High repetition rate rails (several shots per second** for hundreds **of seconds).**
- **High repetition rate switches with high current (several million A versus *750,000* A)**
- **Pulse power conditioners (500 MJ, 5 to 20 ms pulses versus 10 MJ, 100 ms pulses)**
- **Efficiency**
- **Mass**
- **Heat dissipation**

SOURCE: Office of Technology Assessment, 1988.

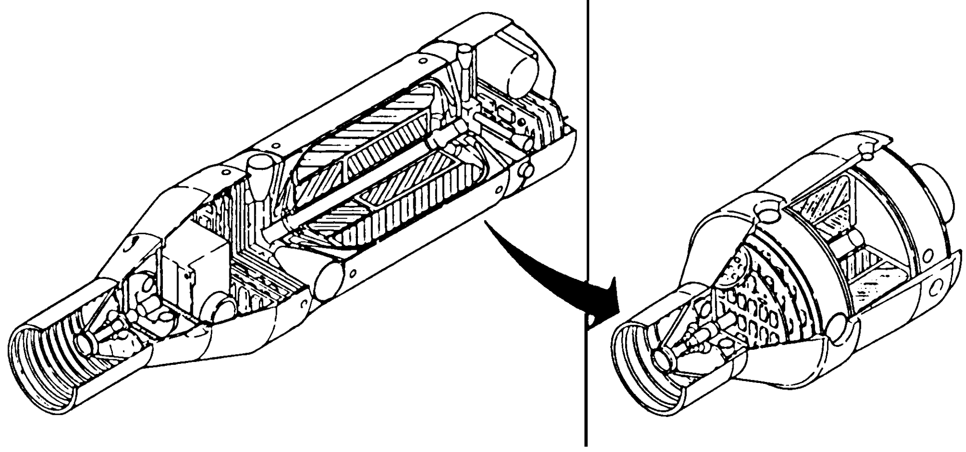
EML Projectile.–If based on current technology for sensors, inertial guidance, communications, and divert propulsion systems, the lightest "smart" projectile would weigh over 10 kg. The total mass must shrink by at least a factor of 5, and the projectile must withstand over 100,000 g's of acceleration. If the projectile could only tolerate 100,000 g's, then the railgun would have to be 112 m long to impart a 15 km/s velocity to the projectile. Higher acceleration tolerance would allow shorter railguns. (200,000 g's would allow a 56-m long gun, etc.)

The SDIO has consolidated the development of light-weight projectiles for all kinetic energy programs into the "Light-weight Exo-atmospheric Projectile" (LEAP) program. Although researchers first saw a need for light-weight projectiles for railguns, the primary initial users of LEAP technology are to be the chemical rocket KEW programs (SBI, ERIS, HEDI). The phase-one LEAP projectile would weigh about 5 kg according to current designs (see figure 5-9), if all component developments met their goals. This projectile would weigh too much for any railgun, and it will therefore not be tested at high acceleration. This technology might evolve into a 2-kg projectile by the early 1990s. In any case, there are no plans now to build a gun big enough to test even the phase-two 2 kilogram projectile.

High Repetition Rate.–A railgun would have to fire frequently during an attack, engaging several targets per second. The penalty for low repetition rates would be additional railguns in the space-based constellation to cover

Figure 5-9.—Lightweight Homing Projectile

LEAP PHASE 1	LEAP PHASE 2



WEIGHT S' STATEMENTS			
LEAP PHASE 1		LEAP PHASE 2	
PAYLOAD	(1 600)	PAYLOAD	(670)
SEEKER	295.0	SEEKER	150.0
IMU	285.0	IMU	70.0
INTEGRATED PROCESSOR	400.0	INTEGRATED PROCESSOR	150.0
COMMAND RECEIVER	100.0	COMMAND RECEIVER	25.0
POWER SYSTEM	325.0	POWER SYSTEM	175.0
STRUCTURE & MISC.	195.0	STRUCTURE & MISC.	100.0
PROPULSION	(3,059.0	PROPULSION	°(1325.0
VALVES & NOZZLES	570.0	VALVES & NOZZLES	375.0
CASE & INERTS	551.0	CASE & INERTS	215.0
PROPELLANT	1818.0	PROPELLANT	690.0
VALVE DRIVERS	120.0	VALVE DRIVERS	45.0
PROJECTILE TOTAL	4659.(	PROJECTILE TOTAL	1995,0

Illustration of planned projectiles for the Lightweight Exoatmospheric Projectile (LEAP) program. This program is developing **projectile technology for both the rocket propelled and electromagnetic launcher (railgun) programs. However, the phase 1 projectile at 5 kg and even the more conceptual phase 2 projectile with a mass projection of 2 kg are too heavy for any existing or planned railguns. There are no plans to test either projectile at the 100,000s of g acceleration necessary for rail gun operation. These projectiles will benefit the SBI, ERIS, and HEDI programs.**

SOURCE: Office of Technology Assessment, 1988.

the threat. Most railguns to date have been fired just once: the rails eroded and had to be replaced after one projectile. Newer systems can fire ten shots per day, and at least one experiment has fired a burst of pellets at a rate of 10/s. Researchers at the University of Texas plan to fire a burst of ten projectiles in 1/6 of a second, or a rate of 60/s.

Key issues for high repetition-rate guns are rail erosion,[18] heat management, and high repetition-rate switches to handle the million-ampere current levels several times per second. Conventional high repetition-rate switches can

[18]New rail designs have shown promise of minimum erosion in laboratory tests; it remains to be proven that rails would survive at weapons-level speeds and repetition rates.

handle up to 500 A today, although one special variable resistance switch tested by the Army carried 750,000 A. An Air Force test successfully switched 800,000 A, limited only by the power supply used. EML systems would have to switch 1 to 5 million A.

EML Power. –An EML would consume high average electrical power and very high peak power during each projectile shot. Consider first the average power requirements: a 1 kg projectile would acquire 112 MJ of kinetic energy if accelerated to 15 km/s. Assuming 40 percent efficiency and 5 shots per second, then the EML electrical system would have to deliver 280 MJ of energy per shot or 1.4 GW of average power during an attack which might last for several hundred seconds. For comparison, a modern nuclear fission power plant delivers 1 to 2 GW of continuous power.

The SP-100 nuclear power system being discussed for possible space application would produce only 100 to 300 kW of power. The only apparent near-term potential solution to providing 2.5 GW of power for hundreds of seconds would be to use something like the Space Shuttle Main Engine (SSME) coupled to a turbogenerator. Assuming 50 percent electrical conversion efficiency, then one could convert the SSME 10 GW of flow energy into 5 GW of average electrical power while the engines were burning.

High average power would not suffice. The electrical energy would have to be further concentrated in time to supply very short bursts of current to the railgun. For example, a 112-m long railgun with 100,000-g acceleration would propel a projectile down its length in about 15 milliseconds (ins) to a final velocity of 15 km/s. The peak power during the shot would be 50 GW.[19] And the EML system designer would like to shorten the 112-m railgun length and increase acceleration, which would mean further shortening the pulse length and increasing peak power.

Several techniques are under consideration to convert the average power from something like the SSME into short pulses. One laboratory approach is the homopolar generator: this device stores current in a rotating machine much like an electrical generator and then switches it out in one large pulse. Existing homopolar generators can supply up to 10 MJ in about 100 ms; therefore, energy storage capacity must increase by a factor of 50 and the pulse length shorten by a factor of 5 to 20.

EML Mass to Orbit.–The mass of an EML system based on today's technology would be excessive. A homopolar generator to supply 280 MJ per pulse would weigh 70 tonnes alone.[20] The rails would have to be long to limit acceleration on sensitive "smart projectiles, which would have to be very strong (massive) to resist the outward forces from the high rail currents. The platform would have to include an SSME-type burst power generator, a thermal management system to dispose of the energy deposited in the rails, divert propulsion to steer the railgun toward each target, and the usual satellite communications and control functions.

Given the early stage of EML research, estimates of total platform mass could be in error by a factor of 10. At this time, a total mass of about 100 tonnes would seem likely, meaning that each EML would have to be launched in several parts, even if the United States developed an Advanced Launch System (ALS) that could carry about 40 tonnes maximum per flight to high inclination orbits. It is conceivable that, in the farther term, superconductive electrical circuits could significantly reduce the mass of an EML. Lighter compulsators (see below) might also reduce EML mass.

Nuclear-Driven Particles.–A nuclear explosion is a potent source of peak power and energy. If even a small fraction of the energy in a nuclear explosion could be converted into kinetic energy of moving particles, then an extremely powerful nuclear shotgun could be im-

[19] For a frame of reference, consider that the total power available from the U.S. power grid is several hundred gigawatts.

[20] Assuming today's energy density for homopolar generators of 4 kJ/kg.

agined. These particles could be used for interactive discrimination as described above, since the particles would slow down light decoys more than heavy RVs With more power, nuclear-driven particles could conceivably destroy targets. This concept is discussed in more detail in the classified version of this report.

Directed-Energy Weapons

Directed-energy weapons (DEW) offer the promise of nearly instantaneous destruction of targets hundreds or thousands of km away. While a KEW system would have to predict target positions several minutes in the future and wait for a high speed projectile to reach the intended target, the DEW could—in principle—fire, observe a kill, and even order a repeat attack in less than a second.

DEW Systems

Although no DEW are planned for phase-one BMD deployment, both ground-based and space-based DEW systems are possible in the next century .21 Candidate DEW systems include:

- free electron lasers (FEL) (ground-based or space-based),
- chemical lasers (space-based),
- excimer lasers (ground-based),
- x-ray laser (pop-up or space-based), or
- neutral particle beam (space-based).

The FEL is the primary SDIO candidate for ground-based deployment (with the excimer laser as a back-up). The hydrogen-fluoride (HF) laser and the neutral particle beam weapon are the primary candidates for space-ased DEWS, although a space-based FEL or other chemical laser concepts might also be possible.

Ground-Based Free Electron Laser (GBFEL). –A GBFEL system would include several ground-based lasers, "rubber mirror" beam directors to correct for atmospheric distortions and to direct the beams to several relay mirrors in high-Earth orbit, and tens to hundreds of "battle-mirrors' in lower Earth orbit to focus the beams on target. It would take several laser sites to assure clear weather at one site all the time. Several lasers per site would provide enough beams for the battle. Ideally these lasers should beat high altitudes to avoid most of the weather and atmospheric turbulence. But the FEL, as currently envisioned, requires very long ground path lengths for beam expansion and large quantities of power.

The logical location for relay mirrors would be geosynchronous orbit, so that the ground-based beam director would have a relatively fixed aim point. The effects of thermal blooming[22] may best be avoided, however, by placing the relay mirrors in lower orbit: the motion of the laser beam through the upper atmosphere as it follows the moving relay mirror would spread the thermal energy over a large area.[23]

Adaptive optics would correct for atmospheric turbulence. The optical system would sense turbulence in real time and continuously change the shape of the beam-director mirror to cancel wave-front errors introduced by the air. A beacon would be placed just far enough in front of the relay satellite that the satellite would move to the position occupied by the beacon in the time it took for light to travel to the ground and back. A sensor on the ground would detect the distortions in the test beam of light from the beacon, then feed the results to the "rubber mirror" actuators. With its wave front so adjusted, the laser beam would pass through the air relatively undistorted.

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[21] SDIO asserts that some versions of DE W could be deployed late in this century. It is examining designs for "entry level" systems with limited capabilities.

[22] "Thermal blooming occurs when a high-power laser beam passes through the atmosphere, heating the air which disturbs the transmission of subsequent beam energy. See the section below on key DEW issues for details.

[23] For example, a 10-m diameter laser beam which tracked a relay mirror at 1,000 km altitude would pass through a clean, unheated patch of air at 10 km altitude after 140 ms. If thermal blooming resulted from relatively long-term heating over a few seconds, then scanning across the sky could ameliorate its effects. While beam energy at altitudes below 10 km would take longer than 140 ms to move to unheated patches of the atmosphere, lower altitude blooming could be more readily corrected by the atmospheric turbulence compensation systems proposed for ground based lasers: atmospheric compensation works best for "thin lens" aberrations close to the laser beam adaptive mirror on the ground.

This concept is discussed further below, under the heading of "Key DEW Issues."

Table 5-2 compares the characteristics of current research FELs with those needed for BMD operations, as derived horn elementary considerations in the American Physical Society study .24 The key figure of merit is beam brightness, defined as the average laser output power (watts) divided by the square of the beam's angular divergence. Brightness is a measure of the ability of the laser beam to concentrate energy on the target (see figure 5-10). Another important figure of merit is the retarget time—the time needed to switch from one target to another.

[24] American Physical Society, op. cit., footnote 1, chapters 3 and 5.

Existing FELs operate in a pulsed mode: the energy is bunched into very short segments, as illustrated in figure 5-11 for the radio frequency linear accelerator (RF linac) and for the induction linear accelerator, two types of accelerators proposed for the FEL. The power at the peak of each pulse is much higher than the average power. In the proposed induction linac FEL, peak power might exceed average power by 60,000 times. But it is the average power that primarily determines weapons effestiveness.[26]

The RF linac experiments to date have produced 10 MW of peak power at 10 µm wave

[25] Short pulses of energy may foster coupling of energy into a target, however, so the average power required from a pulsed laser could, in principle, be less than the average power of a continuous wave (CW) laser. This will be the subject of further SDI research.

Table 5-2.—Characteristics of a Ground-Based FEL Weapons System

	Current status		Operational requirements against a fully responsive Soviet threat[a]
Free Electron Laser	RF	Induction	
Number of laser sites		—	5-8
Wavelength µm)	9-35	8,800	.8 to 1.3
Average power (MW)	*.006*	*.000014*	100 to 1,000
Peak power (MW)	10	1,000[b]	
Beam diameter (m)	(4)[c]	(4)	10 to 30
Brightness (W/sr)	3.6x 10^{14}	1 x 10^{6}	several x1022
Peak brightness (W/sr)	6.3x 10^{17}	4.9 x 10^{13}	d
Beam director:			
Diameter (m)	(4)		10'
Number of actuators	(10^{3})		10^{3} to 10^{4}
Frequency response (Hz)	10^{3}		hundreds
Relay mirrors:			
Number of mirrors	—		3-5?
Diameter (m)	–		10 or more
Altitude (km)	–		tens of thousands
Steering rate (retargets/s)	–		4-1o
Battle-mirrors:			
Number of mirrors:			30-150
Diameter (m)	(4)		10
Altitude (km)	–		1,000-4,000
Steering rate (retargets/s)	–		2-5

operational requirements are taken from American Physical Society, *Science and Technology of Directed-Energy Weapons: Report to the American Physical Society of the Study Group,* April 1987. SDIO disagrees with some of the numbers, but their disagreements are classified and may be found in the classified version of this report. Further, SDIO has identified BMD missions other than dealing with a fully responsive Soviet threat. An "entry-level" system (with a brightness on the order of 10*0). might be developed earlier than the one with the above characteristics and would have less stressing requirements.

[b] Segments of a 3-meter active mirror have been built, and a 4-meter, 7-segment mirror is under construction. Parentheses in this table indicate that the mirror technology exists, but the mirrors have not yet been integrated with the laser.

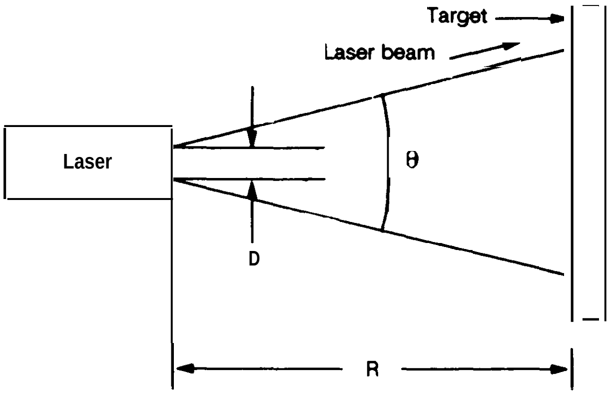
[c] A weapons system would require the *average* power levels listed above. The FEL is a pulsed laser—the power of each pulse is much higher than the average power when the pulses are both on and off. Depending on how targets and pulses interact, these short pulses might be lethal even with lower average power.

[d] Peak brightness, like peak power, is not the relevant measure Of weapons lethality.

[e] The American Physical Society, op. cit., footnote a, estimated that brightnesses on the order of 10^{22} W/sr might be necessary to counter a responsive threat. A 10-meter diameter mirror would be required for the lower power (1 OOMW) FEL module to reach 10^{22} W/sr brightness. The more probable approach would be to combine the beams from ten lo-meter mirrors in a coherent array.

SOURCE: Office of Technology Assessment, American Physical Society Study Group, and Strategic Defense Initiative Organization, 1987 and 19SS.

Figure 5-10. -Illustration of the Relationships Between Laser Parameters and Power Density Projected on a Target



Laser output power = P (watts)
Beam diameter = D (meters)
Divergence angle = θ (radians)
For a diffraction-limited beam,

$$\theta \approx \frac{\lambda}{D} \quad (\lambda = \text{wavelength})$$

Brightness = B

$$B = \frac{P}{\theta^2}$$

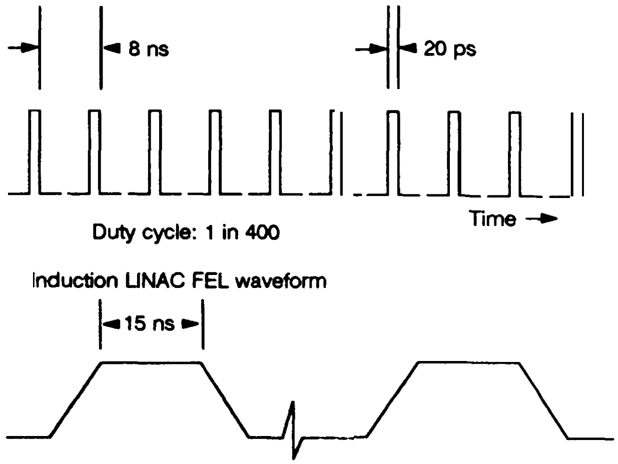
Power **density on target = I (watts/square cm)**

$$I = \frac{B}{R^2}$$

Illustration of the relationships between laser parameters and **power density projected on a target. The key figure of merit for any laser is its brightness. Brightness measures the ability of the laser to concentrate power on a distant target. High brightness requires high laser power and low angular divergence. Low angular divergence in turn requires short wavelength and a large beam diameter. The power density on target is equal to the laser brightness divided by the square of the distance to that target.**

SOURCE: Office of Technology Assessment, 1988.

Figure 5-11 .—FEL Waveforms



Duty cycle: Much lower than radio frequency LINAC

Existing laser waveforms from the radio frequency linear accelerator (RF linac) free electron laser (FEL) and the induction linear accelerator FEL. The laser light is emitted in very short pulses. The peak power during these short pulses would have to be extremely high to transmit high average power to the targets. This peak intensity, particularly for the induction linac FEL, would stress mirror coatings and could induce other nonlinear losses such as Raman scattering in the atmosphere. Therefore, a weapon-grade induction-linac FEL would have to have higher repetition rates, perhaps on the order of 10 kilohertz.

SOURCE: Office of Technology Assessment, 1988.

length, but only 6 kW of average power–which would translate into a brightness 100,000,000 times less than the level needed for a BMD weapon against hardened Soviet boosters.[26] This 6-kW average power was averaged over a 100-microsecond long "macropulse" in a given second.

It should be noted, however, that these experiments were not designed for maximum average power. Low repetition rates were used primariliy for economic reasons. SDIO scientists say that scaling up the number of macropulses from 1/s to 5,000/s is not a serious problem. If correct, this would mean that 30-MW average power could be produced with technology not radically different from today 's. In addition, aground-based weapon would use a wavelength an order of magnitude smaller. The brightness scales as the inverse of the wavelength squared. For a given mirror diameter, then, if a similar power output could be produced at a smaller wavelength, and the high repetition rate were achieved, the brightness would only need to be increased by a factor of about 200 for 30 MW at 1 μm. Accomplish-

[26] This brightness calculation assumes that the beam would be expanded to fill a state-of-the-art 4-m diameter mirror and was diffraction-limited.

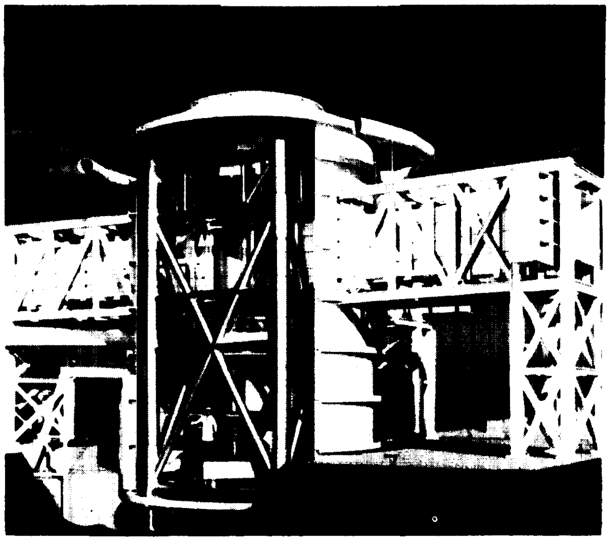


Photo credit: U.S. Department of Defense

Model of ALPHA experimental chemical laser.—This experimental chemical laser and its large vacuum chamber have been constructed by TRW at a test site near San Juan Capistrano, CA. The cylindrical configuration of the laser design may be most suitable for basing in space.

ing both modifications would entail significant development work.

Space-based Chemical Lasers.—Placing high-power lasers directly on satellites would eliminate the needs for atmospheric compensation, redundant lasers to avoid inclement weather, and relay mirrors in high orbits; it would also reduce beam brightness requirements by a factor of 4 to 10 (depending on the wavelength and atmospheric factors) since the atmosphere would not attenuate the beam.[27] These advantages are offset by the engineering challenge of operating many tens or hundreds of lasers autonomously in space and by the possible higher vulnerability of lasers relative to battle-mirrors.

The laser should operate at short wavelength (to keep the mirror sizes small) and should be energy efficient (to reduce the weight of fuel needed in orbit). Although its wavelength band (near 2.8 µm) is rather long, the hydrogen fluoride (HF) laser is the most mature and most efficient laser available today. Table 5-3 compares the characteristics of a potential high performance HF laser BMD system with the current mid-infrared chemical laser (MIRACL) (using deuterium fluoride, or DF) operating at the White Sands Missile Range in New Mexico.[28]

DEW Technology

How DEW Work.—Directed energy weapons would change stationary, stored energy from a primary fuel source into a traveling beam of energy that could be directed and focused on a target. Several stages of energy conversion may be necessary. The challenge is to build an affordable, survivable, and reliable machine that can generate the necessary beam of energy. Lasers can be driven by electrical energy, chemical energy, or nuclear energy.

Free Electron Lasers.—Through 1987, the SDIO chose the FEL research program to receive the most DEW emphasis (recently, SDIO has returned to favoring research in space-based chemical lasers). The FEL uses a relativistic[29] electron beam from an accelerator to amplify a light beam in a vacuum. The key advantage of the FEL is the lack of a physical gain medium: all other lasers amplify light in a solid, liquid, or gas. This gain medium must be stimulated with energy to produce an excited population inversion of atoms or molecules. The fundamental limitation with these lasers is the need to remove waste heat before it affects the optical transparency of the medium. The FEL achieves its gain while pass-

[27] One defense contractor estimated that a space-based chemical laser system, including space transportation, would cost about 10 times less than the proposed ground-based free electron laser weapon system.

[28] The SDIO is also considering lower-performance, "entry level, " space-based chemical lasers for more limited BMD missions.

[29] A beam of particles is deemed "relativistic" when it is accelerated to speeds comparable to a fraction of the speed of light and acquires so much energy that its mass begins to increase measurably relative to its rest mass.

Table 5-3.—Characteristics of an HF Laser Weapons System

	Current status	Estimated operational requirements[a]
Number of laser satellites	—	50-150
Altitude (km)		800-4,000
Beam diameter (m)	1.5[b]	10
Power (MW)	greater than 1	hundreds (single beam)
Brightness (W/sr)	several x 10^{17}[c]	several x 10^{21}
Phased array alternative:		
Number of beams		7
Beam diameter (m)		10
Total power (MW):		100 (14 MW per beam)

aThese numbers derived from first principles, and from American Physical Society, *Science and Technology of Directed-Energy Weapons. Report of ttre American Physical Society Study Group,* April 1987, which contains estimates of booster hardness for a fully responsive threat The SDIO neither confirms nor denies these estimates. Current SDIO estimates may be found in the classified version of this report, In addition, SDIO has identified earlier entry-level systems with less stressing missions and less stressing requirements with brightnesses on the order of 10^{20} W/sr.
bThe LAMP mirror, not yet integrated with a high-power laser, has a diameter of 4 m.
cAssuming perfect beam quality for a multi-megawatt system with the characteristics of the MIRACL laser

SOURCE Office of Technology Assessment, American Physical Society Study Group, and Strategic Defense Initiative Organ i-zation, 1987 and 1988

ing through an electron beam plasma, so much of the "waste heat" exits the active region along with the electron beam at nearly the speed of light.

Two types of electron beam accelerator are currently under investigation in the SDIO program: the radio frequency linear accelerator (RF linac) and the induction linac.[30]

In the RF linac, electrical energy from the primary source is fed to radio-frequency generators that produce an RF field inside the accelerator cavity. This field in turn accelerates low energy electrons emitted by a special source in the front end of the accelerator. The accelerator raises this electron beam to higher and higher energy levels (and hence higher velocity) and they eventually reach speeds approaching that of light. Simultaneously, the electrons bunch into small packets in space, corresponding to the peaks of the RF wave.

This relativistic beam of electron packets is inserted into an optical cavity. There the beam passes through aperiodic magnetic field (called a "wiggler" magnet) that causes the electrons to oscillate in space perpendicular to the beam axis. As a result of this transverse motion, weak light waves called synchrotrons radiation are generated. Some of this light travels along with the electron packets through the wiggler magnets. Under carefully controlled conditions, the electron beam gives up some of its energy to the light beam. The light beam is then reflected by mirrors at the end of the optical cavity and returns to the wiggler magnet synchronously with the next batch of electrons. The light beam picks up more energy from each pass, and eventually reaches high power levels. This type of FEL is an optical "oscillator": it produces its own coherent light beam starting from the spontaneous emission from the synchrotrons radiation.

As more energy is extracted from the electron beam, the electrons slow down. These slower electrons are then no longer synchronized with the light wave and the periodic magnet, so the optical gain (amplification) saturates. To *increase* extraction efficiency, the wiggler magnet is "tapered": the spacing of the magnets or the magnetic field strength is varied so that the electrons continue in phase with the light wave and continue to amplify the beam as energy is extracted.

For high-power weapon applications, the power from an oscillator might be too weak:

[30]"Other types of accelerators are possible for a free electron laser, such as the electrostatic accelerator FEL under investigation at the University of California at Santa Barbara, but the RF linac and induction linac have been singled out as the primary candidates for initial SDI experiments.

the limit for an RF linac FEL oscillator is near 20 MW. In this case additional single-pass amplifiers can boost the beam energy. This system is called a master oscillator power amplifier (MOPA) laser.

In the second type of FEL, the induction linac, large electrical coils accelerate narrow pulses of electrons. The high energy electrons interact with an optical beam as in the RF linac FEL, but the optical beam as currently planned would be too intense to reflect off mirrors and recirculate to pickup energy in multiple passes as in the RF oscillator. Rather, all of the energy transfer from the electron beam to the optical beam would occur on a single pass. This would entail very high gain, which demands very high density electron beams and very intense laser light coming into the amplifier. The induction linac FEL therefore depends on an auxiliary laser to initiate the optical gain process; this limits the tunability of the induction linac FEL to the wavelengths of existing conventional lasers of moderately high power.

The process of converting electron energy into light energy can theoretically approach 100 percent efficiency, although it may take very expensive, heavy, and fragile equipment.[31] Nevertheless, the FEL could achieve very high power levels, and, unlike other lasers, the RF linac FEL can be tuned to different wave lengths by changing the physical spacing or field strength of the wiggler magnets or the energy of the electron beam.[92] Tunability is desirable for ground-based lasers, which must avoid atmospheric absorption bands (wavelengths of light absorbed by the air) if they are to reach into space.

Chemical (EIF) Lasers.–The HF laser derives its primary energy from a chemical reaction: deuterium and nitrogen trifluoride gases react in a device resembling a rocket engine. Hydrogen gas mixes with the combustion products. Chemical energy raises the resulting HF molecules to an excited state, from , which they relax later by each emitting a photon of light energy in one of several wavelength lines near 2.8 μm in the MWIR. A pair of opposing mirrors causes an intense beam of IR energy to build up as each pass through the excited HF gas causes more photons to radiate instep with the previously generated light wave.[33] Some additional electrical energy runs pumps and control circuits.

Excimer Laser.— In an excimer[34] laser, electrical energy, usually in the form of an electron beam, excites a rare gas halide[35] such as krypton fluoride or xenon chloride.[36] These gases then emit in the ultraviolet (UV) region of the spectrum, with wavelengths in the range from.2 to .36pm. This very short wavelength permits smaller optical elements for a given brightness. However, the optical finish on those UV optics would have to be of proportionately higher quality.

Ultraviolet light is also desirable for space applications, since its high energy generally causes more damage to the surfaces of targets than does that of longer-wavelength visible or IR light. One drawback is that internal mirrors resistant to UV radiation damage are more difficult to make. Another is that UV cannot readily penetrate the atmosphere. These obstacles, combined with their relative immaturity and low efficiency, have relegated high power excimers to a back-up role to the FEL for the ground-based BMD laser.

[31] Total system efficiency would probably be about 20 Per@nt 25 percent at best, assuming a reasonably optimistic 50 percent-60 percent efficiency to convert chemical to electrical energy using a rocket-driven turbine, and 40 percent efficiency to generate RF power.

[32] The wavelength of the FEL is proportional to the wiggler magnet spacing and inversely proportional to the square of the electron beam energy. Higher beam energies are necessary for the short wavelengths needed for BMD.

[33] This process of repeat43d radiation in step is called "stimulated emission": the traveling wave of light stimulates the excited molecule to radiate with the same phase and direction as the stimulating energy. The resulting beam of light is "coherent": it can be focused to a very small spot. The term "laser" is derived from the phrase "Light Amplification by Stimulated Electromagnetic Radiation."

[34] Excimer is short for "excited state dimer"; the excitation of these rare gas halides produces molecules that only exist in the excited state, unlike other lasing media which decay to a ground state after emitting a photon of light.

[35] A "halide" is a compound of two elements, one of which is a halogen: fluorine, chlorine, iodine, or bromine.

[36] Krypton fluoride produces a wavelength too short to penetrate the atmosphere; for ground-based applications, xenon chloride would be of interest.

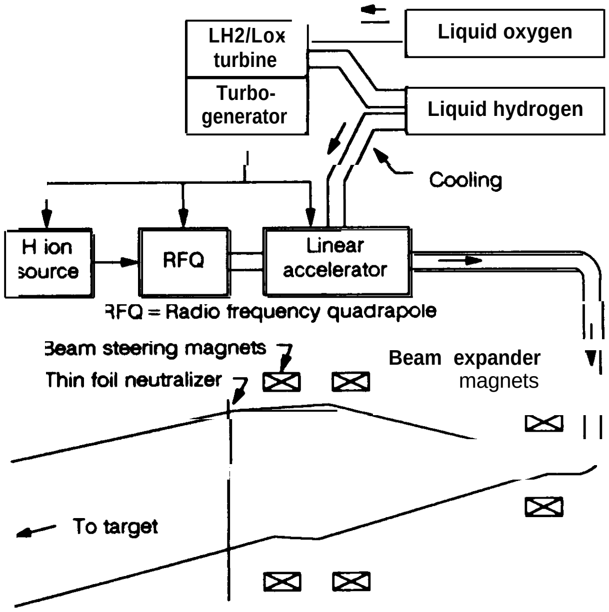
Passing a laser beam through a Raman gas cell can improve its quality. This cell, typically filled with hydrogen gas, can simultaneously shift the laser frequency to longer wavelengths (for better atmospheric propagation), combine several beams, lengthen the pulse (to avoid high peak power), and smooth out spatial variations in the incoming beams. A low-power, high quality "seed" beam is injected into the Raman cell at the desired frequency. One or more pump beams from excimer lasers supply most of the power. In the gas cell, Raman scattering transfers energy from the pump beams to the seed. This process has been demonstrated in the laboratory with efficiencies up to 80 percent.

X-ray Laser.—A nuclear explosion generates the beam of an x-ray laser weapon. Since this type of laser self-destructs, it would have to generate multiple beams to destroy multiple targets at once. It has been proposed that x-ray lasers would be based in the "pop-up" mode; their launch rockets would wait near the Soviet land mass and fire only after a full-scale ICBM launch had been detected. Since the x-rays could not penetrate deeply into the atmosphere unless self-focused, the earliest application for the x-ray laser would likely be as an ASAT weapon.

Neutral Particle Beam (NPB) Weapon.—The NPB weapon, like a free electron laser, would use a particle accelerator (see figure 5-12). This accelerator, similar to those employed in high energy physics experiments, would move charged hydrogen (or deuterium or tritium) ions to high velocities. Magnetic steering coils would aim the beam of ions toward a target. As the beam left the device, a screen would strip the extra electrons off the ions, resulting in a neutral or uncharged beam of atoms.[37]

Unlike laser beams, which deposit their energy on the surface of the target, a neutral particle beam would penetrate most targets, causing internal damage. For example, a 100-MeV particle beam would penetrate up to 4

Figure 5-12.—Schematic of a Neutral Particle Beam Weapon



Schematic of a neutral particle beam weapon. Primary power might be generated by firing a rocket engine, similar to the Shuttle main engine, coupled to an electrical generator. Alternately, the hydrogen and oxygen could be combined in a fuel cell to produce electricity. The resulting electrical current would drive the accelerator that would produce a beam of negatively charged hydrogen ions. This negatively charged beam would be expanded and directed toward the target by magnets. Just before leaving the device, the extra electron on each hydrogen ion would be stripped off, leaving a neutral particle beam that could travel unperturbed through the earth's erratic magnetic field.

SOURCE: Office of Technology Assessment, 1988

cm into solid aluminum and a 200-MeV beam would deposit energy 13 cm deep.[38] These penetrating particles could damage sensitive circuits, trigger the chemical high explosives in nuclear warheads, and-at high enough incident energy levels—melt metal–components. Shielding against neutral particle beams would be difficult; imposing a large weight penalty.

As mentioned in chapter 4, the NPB may be usable first as an interactive discriminator. The beam of energetic hydrogen atoms would dislodge neutrons from massive RVs (the dis-

[37] A charged beam could not be aimed reliably, since it would be deflected by the Earth's erratic magnetic field, so the beam must be uncharged or neutral.

[38] See W. Barkas and M. Berger, *Tables ofEnergy Losses and Ranges of Heavy Charged Particles,* (Washington, DC: NASA, 1964).

criminator NPB would presumably dwell on each RV and decoy for too short a time to damage the RV). Separate satellites with neutron detectors would determine which targets were RVs and which were light-weight decoys. The NPB technology development would be the same for the weapon and the interactive discrimination programs, giving it multi-mission capability.

Current Status of DEW.–Directed energy weapons are at various stages of development as discussed below, but none could be considered ready for full-scale engineering development or deployment in the next decade.[39]

The characteristics of three potential DEW systems are summarized in table 5-4. A key figure of merit is the brightness of the beam. Precisely what brightness would destroy different targets is still under investigation: the SD I research program is measuring target lethality for different wavelengths and for different classes of targets. The brightness levels of table 5-4 are derived from physical first principles and assume that the Soviets could convert their missiles to hardened, solid-fueled boosters by the time DEWS could be deployed.[40]

[39] SDIO has recently been considering "entry-level" options that it currently considers feasible for phase-two deployment.

[40] SDIO is considering "entry level" DEWS that would have much lower brightness and might be effective against today's more vulnerable boosters. A synergistic mix of KEW-DEW boost-phase intercept capability and DEW discrimination is being considered by SDIO as possible parts of a phase-two system.

The Accelerator Test Stand (ATS) neutral particle beam experimental accelerator at Los Alamos National Laboratory is the weapon candidate closest to lethal operating conditions: its brightness would need to rise by about a factor of 10,000 to assure destruction of electronics inside an RV at typical battle ranges (thousands of km). However, in this kill mode, it maybe hard to determine whether the electronics actually had been destroyed. Another factor of 10 to 100 might be needed to produce visible structural damage.

The MIRACL DF chemical laser operating at White Sands has greater than 1 megawatt output power, but its relatively long wavelength, the challenge of unattended space operation, and the uncertainty of scaling this laser to the power levels necessary for ballistic missile defense would make a deployment decision now premature. The brightness of an HF or DF laser would have to be increased by a factor of 10,000 to 100,000 over current levels to be useful against responsively hardened Soviet boosters. However, an "entry-level" system that might be useful against current boosters would entail an increase in brightness of only several hundred to several thousand times.

To test some aspects of a space-based HF laser, TRW is installing its "Alpha" laser in a large space-simulation chamber near San Juan Capistrano, California. The Alpha laser uses a cylindrical geometry (MIRACL uses lin-

Table 5.4.—Characteristics of Directed Energy Weapons Against a Fully Responsive Soviet Threat[a]

	FEL—ground-based	HF—space-based	NPB—space-based
Primary energy source	Electric	Chemical	Electric
Wavelength or energy	0.8-1.3 μm	2.7 μm	100-400 MeV
Required brightness (W/sr)	Several $\times 10^{22}$	Several $\times 10^{21}$	Several $\times 10^{19}$ (for electronics kill)
Current brightness (W/sr)	Several $\times 10^{14}$ (considering unintegrated components)	Several $\times 10^{17}$[b] (potential for about 10^{10} if unintegrated components considered)	10^{15}-10^{16} (considering unintegrated components)
Minimum penetration altitude (km)	About 30	About 30	130-170

[a] The numbers in this table are obtained from the American physical Society, *Science and Technology of Directed-Energy Weapons: Report Of the American Physical Society Study Group,* April 1987, and apply to an advanced BMD system against a responsive threat. The estimates are neither confirmed nor denied by SDIO. SDIO has identified other BMD missions for which lower "entry-level" systems with lower specifications (on the order of 10^{10} W/sr) would be adequate.
[b] Assuming perfect beam quality for a system with the characteristics of the MIRACL laser.

SOURCE: Office of Technology Assessment, American Physical Society Study Group, and Strategic Defense Initiative Organization, 1987 and 1988.

ear flow) with the supersonic gas flowing outward from a central 1.1-m diameter cylinder formed by stacking rings of carefully machined nozzles. The laser beam will take the form of an annulus passing just outside the radially directed nozzles. A complex aspheric mirror system will keep the laser beam within this narrow ring. The goal of this program is to demonstrate multi-megawatt, near-diffraction limited operation in 1988.

The brightness of a 4-m diameter (the size of the Large Aperture Mirror Program mirror), perfect, diffraction-limited beam[41] from, for example, a 1-MW laser, would be over 10^{18} watts/steradian (W/sr). The Alpha laser was designed to be scaled to significantly higher levels by stacking additional amplifier segments. It would take a coherent combination of many such lasers to make a weapon able to engage a fully responsive missile threat.

Chemical lasers to meet a responsive Soviet missile threat would need brightnesses of 10^{21}-10^{22} W/sr. The level needed would depend on the target dwell and retarget times. These times, in turn, depend on the laser constellation size and geometry, booster burn time and hardness, and number of targets which must be illuminated per unit time. If the Soviets were to increase the number of ICBMs in a particular launch area or decrease booster burn times, then the laser brightness needed would increase.

The brightness of aground-based FEL would have to increase by a factor of 4 to 10 to account for energy losses as the beam passed through the atmosphere and travelled to and from relay mirrors in space. Several free electron lasers have been built. None has operated within a factor of 100 million (10^8) of the lethal brightness levels needed for a fully-responsive BMD system. Part of the reason is the low repetition rate of the pulses in experimental machines. For example, one experiment ran with the accelerator operated at a rate of one electron beam pulse every two seconds. Future accelerators will probably increase this rate to thousands of pulses per second. This will increase average brightnesses accordingly, although, as previously discussed, several more factors of 10 improvement would be needed.

Lawrence Livermore National Laboratory is conducting experiments with an FEL based on an induction linear accelerator (linac). Boeing Aerospace is constructing an RF linac FEL, based on technology developed by Boeing and Los Alamos National Laboratory.

Initial experiments on the Livermore FEL in 1985 produced microwave beams at 8.6 mm wavelength with peak powers of 100 MW. More recently, the peak power risen to 1.8 GW ($1.8x10^9$W),[42] although this intensity lasts for only 15 nanoseconds ($15x10^{-9}$s); the average power at the repetition rates of one shot every 2 seconds was only 14 W. Scaling to shorter wavelengths demands higher quality and very high-energy electron beams. Livermore Laboratory achieved FEL lasing at 10 µm in the far IR with its "Paladin" laser experiment in late 1986. Boeing and a TRW/Stanford University collaboration have operated 0.5 µm visible lasers, but at low average power levels.

The Boeing RF linac FEL has the advantage of multiple optical passes through the wiggler of the optical oscillator. This means that high gain is not necessary, as it is with single-pass induction linacs.[43] The RF linac also has more tolerance of variations in electron beam quality or emittance. The emittance of the RF linac electron beam could grow (i.e., deteriorate) by almost a factor of 10 without deleterious effects. In contrast, the induction linac electron beam cannot increase in emittance by more than a factor of two without degrading optical beam brightness.[44] However, there has been more uncertainty as to whether RF linacs could be scaled to the high current levels needed for BMD. Induction linacs, on the other hand,

[41] See American Physical Society, op. cit., footnote 1, p. 179.

[42] Andrew M. Sessler and Douglas Vaughan, "Free-Electron Lasers, " *American* Scientist, vol. *75,* January-February, 1987, p. *34.*

[43] The RF linac might require single-pass amplifiers in addition to their multi-pass oscillators (MOPA configuration) to achieve weapons-class power levels.

[44] Private communication, John M.J. Madey, 1987.

have inherently high-current capability. Recently, the two FEL concepts have appeared on the whole to compete closely with one another.

Excimer lasers have been utilized for lower power research and some commercial applications. The UV energy from an excimer laser is generally more damaging than visible or IR energy. However, UV light can also damage mirrors and other optical components within the laser system, making high-power operation much more difficult. Scaling to higher power is possible, but SDIO has judged the excimer program less likely to succeed, and has cut it back. The Air Force ASAT program is funding continued excimer laser research jointly with SDIO.

Los Alamos National Laboratory researchers have conducted NPB-related experiments on their ATS. They have produced a current level of 0.1 A at 5 MeV. Rocket-borne tests of parts of a NPB system were planned for the late 1980s. The SDIO had planned a series of full space tests to begin in the early 1990s, including a NPB accelerator with a target satellite and a neutron detector satellite as part of the interactive discrimination experimental program. Recently, scheduling of these tests has been delayed due to funding constraints.

Key DEW Issues.–With such a wide gap between operational requirements and the current status of DEW, many key technical issues remain. DEW research over the next 10 to 20 years could resolve some issues judged crucial today, but could also uncover other, unforeseen, roadblocks. Some of the current issues of concern (large mirrors, pointing and tracking, and lethality measurements) are generic to all laser systems, while others are specific to particular weapon systems.

Large Mirrors.–All laser systems (except the x-ray laser) need very large mirrors to focus the beam to a small spot at the target.[45]

[45] Spot size is inversely proportional to mirror diameter. Laser brightness, the primary indicator of weapon lethality, increases as the square of mirror diameter. Thus doubling the mirror size from 2 meters to 4 meters would increase laser brightness by a factor of 4.

This is true for both ground-based lasers with multiple relay mirrors in space and for space-based lasers with the mirror adjacent to the laser. In either case, the size of the last mirror (closest to the target) and its distance from the target determine the size of the laser spot focused on that target. To achieve the brightness levels of 10^{21} to 10^{22} W/sr for BMD against a fully responsive threat, laser mirrors would have to be at least 4 m (assuming mirrors were ganged into coherent arrays), and preferably 10 to 20 m, in diameter.

The largest monolithic telescope mirrors today are about 5 m in diameter (Mt. Palomar), and the largest mirror built for space application is the Hubble Space Telescope at 2.4 m. The Hubble or Palomar mirror technologies would not simply be scaled up for SD I applications. The current trend both in astronomy and in military applications is to divide large mirrors into smaller segments. Electro-mechanical actuators within the mirror segments adjust their optical surfaces so that they behave as a single large mirror.

Even for these segments, direct scaling of old mirror manufacturing techniques using large blocks of glass for the substrate is not appropriate: these mirrors must weigh very little. They must be polished to their prescribed surface figure within a small fraction of the wavelengths they are designed to reflect. Brightness and precision make opposite demands: usually, a thick and relatively heavy substrate is necessary to keep good surface figure. SDIO has developed new technologies to reduce substrate weight substantially.

Two segments of a 3-segment, 3-m mirror (HALO) have been built. The 7-segment, 4-m mirror (LAMP) is now assembled and currently being tested. One segment of a l0-m mirror is to be built by 1991, but there are no current plans to assemble a complete 10-m mirror. Recently, the SDIO has begun tests of the lightweight LAMP mirror, designed for space-based lasers.

Durable, high-reflectivity mirror coatings are essential to prevent high laser power from damaging the mirrors. The largest mirror that has been coated with a multi-layer dielectric coating to withstand high energy-density levels is 1.8 m in diameter. Multi-layer dielectric coatings are generally optimized to produce maximum reflectivity at the operating wavelength. Their reflectivity at other wavelengths is low (and transmission is high), meaning that off-wavelength radiation from another (enemy) laser could penetrate and damage them.[46] These coatings may also be susceptible to high-energy particle damage in space, either natural or man-made.

Finally, the optical industry must develop manufacturing techniques, infrastructure, and equipment to supply the hundreds of large mirrors for BMD DEW deployment. The SDI research program has targeted mirror fabrication as a key issue, and progress has been good in the last few years. Techniques have been developed to fabricate light-weight, segmented mirrors with hollow-cored substrates and actuators to move each segment to correct for surface figure errors.

These active mirrors could correct both for large-scale manufacturing errors and for operational changes such as distortions due to thermal warping. They could even correct for broad phase errors in the laser beam. The price would be added complexity. A complex electro-mechanical-optical servo system would replace a simpler static mirror. And, to make the necessary corrections, another complex wave-front detection system would measure the phase distortions of the laser beam in real time.

With reliable active mirrors, it might be possible to coherently combine the output energy from two or more lasers. The brightness of "N" lasers could theoretically be increased to "N^2" times that of a single laser with this coherent addition. (See section below on chemical lasers for more details.)

Pointing, Tracking and Retargeting Issues. —A DE W beam must rapidly switch from one target to the next during a battle. Assuming that each DEW battle-station within range of Soviet ICBMs would have to engage 2 ICBMs per second,[47] then the beam would have to slew between targets in 0.3 s to allow 0.2 s of actual laser dwell time. In addition, the mirror would have to move constantly to keep the beam on the target: the target would move 1.4 km during 0.2s exposure, and the beam would have to stay within a 20- to 30-cm diameter spot on the moving target.

Large 10- to 30-meter mirrors could move continuously to track the general motion of a threat cloud, but jumping several degrees to aim at a new target in 0.3 s would be rather difficult.[48] One solution would be to steer a smaller, lighter-weight secondary mirror in the optics train, leaving the big primary mirror stationary. This approach would yield only limited motion, since the beam would eventually walk off the primary mirror; in addition, the smaller secondary mirror would be exposed to a higher laser intensity, making thermal damage more difficult to avoid.

Alternatively, small-angle adjustments could be made with the individual mirror segments that would constitute the primary mirrors. These mirror segments would probably have mechanical actuators to correct for gross beam distortions and thermal gradient-induced mirror warpage. Again, moving individual mirror segments would produce only limited angular motion of the total beam.[49]

[46] Dielectr'c coatings are nominally transmissive off the main wavelength band, but there are always defects and absorbing centers that absorb energy passing through, often causing damage and blow-off. At best the transmitted energy would be deposited in the substrate, which would then have to be designed to handle the high power density of offensive lasers.

[47] Of a laser battle-station fleet of 120, perhaps 10 to 12 would be within range of the missile fields. Assuming that average Soviet booster bum times were in the range of 130 seconds by the time a DEW system could be deployed, and allowing 30 seconds for cloud break and initial track determination, then each DEW platform in the battle space would have to engage an average of about 130 ICBMs in 100 seconds. This required targeting rate of about 1.3 per second could be increased by factors of 2 to 5 or more if the Soviet Union decided to deploy more ICBMs, and if they concentrated those extra ICBMs at one or a few sites. For this discussion, a figure of 2 per second is taken.

[48] Slewing requirements can be minimized by using appropriate algorithms.

[49] Alternate concepts are being investigated to allow retargeting at large angles with steerable secondary mirrors.

The mirror servo system would have to accomplish these rapid steering motions without introducing excessive vibration or jitter to the beam. To appreciate the magnitude of the steering problem, consider that a vibration that displaced one edge of a 10-m mirror by 1 micrometer (1 µm—40 millionths of an inch or twice the wavelength of visible light) would cause the laser to move one full spot diameter on the target.[50] This small vibration would cut the effective laser brightness in half. Allowable jitter is therefore in the 20 nanoradian, or one part in 50 million, range. Since any servo system would undoubtedly exceed these jitter limits immediately after switching to a new target, there would be a resettling time before effective target heating could begin. This resettling time would further decrease the allowable beam steering time, say from 0.3 s to 0.2 or 0.1 s.

Non-inertial methods of steering laser beams are under investigation. For example, a beam of light passing through a liquid bath which contains a periodic acoustical wave is diffracted at an angle determined by the acoustical frequency. By electronically changing the acoustical frequency in the fluid, the laser beam could be scanned in one direction without any moving parts. Two such acousto-optic modulators in series could produce a full two-dimensional scanning capability.

Alternatively, the laser beam could be reflected off an optical grating that diffracted it at an angle that depended on its wavelength. If the laser wavelength could be changed with time, then the beam could be scanned in one direction. Most of these non-inertial scanning techniques could not operate at weapons level laser power without damage. Others place constraints on the laser, such as limiting tunability.

Approximate beam steering and retargeting levels are summarized in table 5-5. These parameters would vary with specific weapons design, system architecture, and assumed threats. In general, demands on beam steering speed and precision would increase if the DEW range were extended (by deploying fewer than the 120 battle stations assumed here, for example), or if the Soviets increased the offensive threat above 1,400 ICBMs with average burn time of 130 s assumed above.

Table 5-5.—Possible Beam Steering and Retargeting Requirements for Boost-Phase Engagement

Retargeting rate	2 targets/second
Retarget time	0.1 to 0.2 seconds
Jitter resettling time	0.1 to 0.2 seconds
Average laser dwell time	0.2 seconds
Laser angular beamwidth[a]	120 nanoradians
Allowable beam jitter	20 nanoradians

[a]The diffraction. limited beam spread for a 1 µm laser with a 10 m diameter mirror is 120 nr.

SOURCE: Office of Technology Assessment, 1988.

Beam steering and retargeting needs for post-boost and midcourse battle phases could be more stressing if boost-phase leakage were high and discrimination were not reasonably effective. In general there would be more time for midcourse kills, and more DEW platforms would engage targets, but the hard-shelled RVs would withstand much more laser irradiation and hence impose longer dwell times. Lasers do not appear likely candidates for midcourse interception of RVs.

A neutral particle beam weapon (NPB) would not have to dwell longer on RVs than on boosters or PBVs, since energetic particles would penetrate the RV. Without midcourse discrimination, the NPB system might have to kill from 50,000 to 1,000,000 objects surviving the boost phase, and a weapon platform would have to kill an average of 3 to 50 targets per second. At the other extreme, with effective discrimination, each NPB platform in the battle might have to engage only one RV or heavy decoy every 20 s.[51]

Atmospheric Turbulence and Compensation for Thermal Blooming. -One current DEW candidate is the ground-based free electron la-

[50]This assumes a 20-cm spot diameter on a target 1,000 km away, or an angular motion of 200 nanoradians.

61 Assume 6,000 RVs, 6,000 heavy decoys, and 10 Percent leakage from the boost phase defense. If the discrimination system reliably eliminated all light decoys and debris, then, with 30 of the 120 DEW platforms in the midcourse battle, each platform would engage, on the average, one target every 22.5 seconds.

ser. The beam from this laser would be directed to a mirror in space that would reflect the beam to "fighting mirrors" closer to the targets. The laser beam would be distorted in passing through the atmosphere, for the same reason that stars "twinkle." If not corrected, atmospheric distortion would scramble the beam, making it impossible to focus with sufficient intensity to destroy ICBM boosters.

Techniques have been developed to measure this distortion of the optical wave front and to modify the phase of low power laser beams to nearly cancel the effects of the turbulent atmosphere. To correct distortion, the mirror is manufactured with a flexible outer skin or with separate mirror segments. Mechanical actuators behind the mirror surface move it to produce phase distortions that complement phase errors introduced by the atmosphere. This "rubber mirror" must continuously adjust to cancel the effects of atmospheric turbulence, which varies with time at frequencies up to at least 140 hertz (cycles per second).

To measure atmospheric distortion, a test beam of light must be transmitted through the same patch of atmosphere as the high power laser beam. For the BMD application, this test beam would be projected from a point near the relay mirror in space, or a reflector near that relay mirror would return a test beam from the ground to the wave-front sensing system. Signals derived from the wave-front sensor computer in response to the test beam would drive the mirror actuators to correct the high-power laser beam.

The wave-front sensor must generate a coherent reference beam to compare with the distorted beam, as in an interferometer. One technique, called shearing interferometry, causes two slightly displaced versions of the incoming distorted image to interfere. A computer then deduces the character of the distorted wave front by interpreting the resulting interference fringes,

Another wave-ront sensor system under investigation filters part of the incoming reference beam to produce a smooth, undistorted wave front. This clean wave front can then be combined with the distorted wave front, producing interference fringes that more clearly represent the atmospheric distortion. Unfortunately the energy levels in the filtered wave front are too low, so an operational system might need image intensifiers.

Atmospheric compensation of low power beams has been demonstrated in the 1aboratory and in tests during late 1985 at the Air Force Maui Optical Station (AMOS) in Hawaii. In this test, an argon laser beam was transmitted through the atmosphere to a sounding rocket in flight. A reflector on the sounding rocket returned the test signal. Wave-front errors generated on Maui drove a "rubber mirror" to compensate for the turbulence experienced by a second Argon laser beam aimed at the rocket. A set of detectors spaced along the sounding rocket showed that this laser beam was corrected to within a factor of two of the diffraction limit.

Successful atmospheric compensation will entail resolution of two key issues: thermal blooming and fabrication of large, multi-element mirrors. As a high-power laser beam heats the air in its path, it will create additional turbulence, or "thermal blooming," which will distort the beam. At some level, this type of distributed distortion cannot be corrected. For example, if thermal blooming causes the laser beam to diverge at a large distance from the last mirror, then the test beam returning from the relay satellite would also spread over a large area and would not all be collected by the wave-front sensor. Under these conditions, complete compensation would not be possible.

Laboratory tests of thermal blooming were planned at MIT's Lincoln Labs and field-testing was planned for early 1989 using the high-power MIRACL laser at the White Sands Missile Range. The latter series of tests is on hold due to lack of funding.

The mirror for a BMD FEL would need 1,000 to 10,000 actuators for effective atmospheric compensation.[52] Experiments to date have used cooled mirrors with a relatively small

[52]American Physical Society, op. cit., footnote 1, p. 190.

number of elements, and Itek is currently building a large uncooled mirror with many more.

Nonlinear optical techniques may offer an alternative to the active-mirror correction of atmospheric turbulence. Laboratory experiments at low power have already demonstrated beam cleanup by stimulated Brillouin scattering, for example. In this technique, a beam of light with a wave front distorted by the atmosphere enters a gas cell. The beam passes partially through this gas and is reflected back with complementary phase distortion. This complementary or "conjugate" phase exactly cancels the phase distortions introduced by the atmosphere. The key is to amplify the phase conjugate beam without introducing additional phase errors. If perfected, this approach would eliminate moving mirror elements.

Target Lethality.— One term in the DEW effectiveness equation is the susceptibility of current and future targets to laser and neutral particle beams. Current U.S. missile bodies have been subjected to HF laser beams in ground-based tests, and various materials are being tested for durability under exposure to high-power laser light.[53] Laser damage varies with spot size, wavelength, pulse length, polarization, angle of incidence, and a large range of target surface parameters, making lethality test programs complex.[54] FEL beams with a series of very short but intense pulses may produce an entirely different effect than continuous HF chemical laser beams.

Measuring the lethality of low-power neutral particle beam weapons intended to disrupt electronics could be more complicated. Damage thresholds would depend on the electronics package construction. However, current plans call for particle beam energy density which would destroy virtually any electronic system.[55] The kill assessment issue for NPB weapons would then become one of hit assessment: the system would have to verify that the particle beam hit the target.

FEL.-The two types of FEL systems (induction linac and RF linac) face different sets of key issues (table 5-6). The induction linac FEL has the potential of very high power, but all of the laser gain must occur on one pass through the amplifier as currently designed. (Almost all other lasers achieve their amplification bypassing the beam back and forth between two mirrors, adding up incremental energy on each pass.)

To achieve BMD-relevant power levels on one pass, the FEL beam diameter must be very small, on the order of a millimeter (mm). Furthermore, the beam must be amplified over a very long path, on the order of 100 m. But a millimeter-diameter beam would naturally expand by diffraction over this long path length,[56] so the induction linac must utilize the electron beam to guide and constrain the light beam while it is in the wiggler magnet amplifier, much like a fiber optic cable. This optical guiding by an electron beam has been demon-

[53]In one highly publicized test at the White Sands Missile Range, a strapped-down Titan missile casing, pressurized with nitrogen to 60 pounds per square inch pressure to simulate flight conditions, blew apart after exposure to the megawatt-class MIRACL laser.

"Computer models have been developed to help predict target lethality, and these models will be refined and correlated with ongoing lethality measurements.

'What is, the NPB would be designed to deliver 50 J/gin at the target, whereas 10 J/gin destroys most electronics (see American Physical Society, op. cit., footnote 1, p. 306. This would assure electronics kill unless massive shielding were placed around key components.

[56]A 1-mm beam of unconstrained 1-μm light would expand to 120 mm after traveling 100 m.

Table 5.6.–Key Issues for Free Electron Lasers (FEL)

For induction linear accelerator driven FELs:
- —Electron beam guiding of the optical beam
- —Generation of stable, high current, low-emittance e-beams
- —Scaling to short wavelengths near 1 µm
- —Raman scattering losses in the atmosphere

For radio frequency accelerator-driven FELs:
- —Scaling to 100 MW power levels
- —Efficiency
- —Mirror damage due to high intercavity power
- —Cavity alignment

For any FEL:
- —Long cavity or wiggler path lengths
- —Sideband instabilities (harmonic generation)
- —Synchrotron/betatron instabilities (lower efficiency)

SOURCE: Office of Technology Assessment, 1988, strated, but not under weapon-like FEL conditions.

Two other disadvantages derive from this narrow, intense beam of light produced by the induction linac FEL. First, the beam is so intense that it would damage any realizable mirror surface. The current plan is to allow the beam to expand by diffraction after leaving the FEL, traveling up to several km in an evacuated tunnel before striking the director mirror which would send the beam to the relay mirror in space.

A second disadvantage of such intense pulses of light is that they would react with the nitrogen in the atmosphere by a process called "stimulated Raman scattering. " Above a threshold power density, the light would be converted to a different frequency which spreads out of the beam, missing the intended target.[57] Again, this effect could be ameliorated by enclosing the beam in an evacuated tube, allowing it to expand until the power density were low enough for transmission through the atmosphere to the space relay. On the return path to the target, however, the beam would have to be focused down to damage the target.

The experimental induction linac at Livermore currently uses a (conventional, non-FEL) laser-initiated channel to guide the electron beam before it is accelerated. This beam has drifted several millimeters laterally during the FEL pulse in initial experiments, severely limiting FEL lasing performance because the electron beam does not remain collinear with the FEL laser beam.

The RF linac FEL, as currently configured, has shorter pulse lengths (20 picosecond v. 15 nanoseconds for the induction linac FEL) but much higher pulse repetition rates (125 MHz v. 0.5 MHz[58]), giving it higher duty cycle and lower peak intensity for a given output average power level. It is uncertain whether the RF linac can be scaled up to produce power levels which seem probable for the induction linac. By adding a set of power amplifiers in series, it might be possible to reach the power needed for a lethal laser weapon with an RF linac FEL.

The RF linac generates very high power levels inside the optical cavity. Mirror damage is therefore an issue, as is the problem of extracting energy out of the cavity at these high power levels. Cavity alignment is also critical: the mirrors must be automatically aligned to maintain path-lengths within micrometers over many tens of meters during high-power operation.

The RF linac currently has low efficiency. In 1986, Los Alamos National Laboratory and a TRW-Stanford team demonstrated an energy recovery technique whereby much of the unused energy in an electron beam was recovered after the beam passed through a wiggler-amplifier. In principle, this energy could be coupled back to the RF generator to improve efficiency in an operational system. At the higher optical energy levels envisaged for the amplifiers, the RF linac amplifier should achieve 20 percent to 25 percent conversion efficiency, making energy recovery less advantageous.

An FEL would tend to be fragile. Accelerators are notorious for demanding careful alignment and control, taking hours of manual alignment before operation. Major engineering developments in automatic sensing and control would be necessary before an FEL could become an operational weapon. Los Alamos is working to automate its ATS particle beam accelerator; FEL systems would have to incorporate similar automation, with the added complexity of optical, as well as accelerator, alignment.

An FEL may suffer from electron beam (e-beam) instabilities. For example, unwanted longitudinal e-beam excursions could create "sideband instabilities," in which part of the optical energy would be diverted to sideband frequencies. Laser light at these extraneous frequen-

[57] The Raman threshold for stimulated gain in nitrogen gas at one μm light is about 1.8 MW/cm^2. Above this power density, the atmosphere becomes a single-pass nitrogen laser: much of the beam energy is converted to different (Stokes and anti-Stokes) wavelengths which diverge and cannot be focused on the target.

[58] The induction linac at Livermore could be operated up to 1 kHz for up to 10 pulses. An operational linac FEL would have a repetition rate as high as tens of kilohertz.

cies could damage optical components designed to handle high power only at the main lasing frequency. Such sideband frequencies have been observed in FEL experiments. Lateral motion of the e-beam, called "synchrotron/betatron instabilities" could reduce FEL efficiency, although calculations indicate that this should not be a problem.

Chemical Laser Issues.—The chemical HF laser has some disadvantages relative to the FEL. Its longer wavelength (2.8-pm range) would demand larger mirrors to focus the beam on target. In general, targets would reflect a higher percentage of IR light than visible or, particularly, UV light. Hence, for a given mirror size, an HF laser would have to generate *7* to 10 times more power than an FEL laser operating at one µm, or 80 to 200 times more power than a UV laser, to produce the same power density at the target.

Chemical laser experts do not believe that an individual HF laser could be built at reasonable cost to reach the 10^{21} to 10^{22} W/sr brightness levels needed for BMD against a responsive threat, since the optical gain volume is limited in one dimension by gas flow kinetics, and by optical homogeneity in the other directions. However, by combining the outputs from many HF lasers, it might be possible to produce BMD-capable HF arrays (table 5-7).

These beams must be added coherently: the output from each laser must have the same frequency and the same phase.[59] Controlling the phase of a laser beam is conceptually easy, but difficult in practice–particularly at high power and over very large apertures. Since an uncontrolled HF laser generates several different frequencies in the 2.6 to 2.9 µm band, the laser array would have to operate on one spectral line, or one consistent group of lines.

Table 5-7.—Key Issues for the HF Chemical Laser

Coherent beam combination: (many HF laser beams would have to be combined to achieve necessary power levels)	
Required beam brightness against a responsive threat . . .	**several x 10^{21} W/sr[a]**
Reasonable HF Laser brightness for a single large unit (10 MW power and 10-m mirror).	**8.6 x lo"**
Coherent Array of seven 10 MW/10-m HF lasers	**$4.2x10^{21}$**

[a]The American Physical Society, *Science and Technology of Directed-Energy Weapons: Report of the American Physical Society Study Group,* April 1967, p. 55, estimated hardness for a responsive threat to be well in excess of 10 kJ/cm². Given a range of 2,000 km and a dwell time of 0.2s, the denoted brightness is appropriate.

SOURCE: Office of Technology Assessment, 1966.

Three coherent coupling techniques have been demonstrated in the laboratory:

1. Coupled Resonators—the optical cavities of several lasers are optically coupled, so they all oscillate in phase;
2. Injection Locked Oscillators-one low power oscillator output light beam is injected into the optical cavity of each laser;
3. Master Oscillator/Power Amplifier (MOPA) —each laser is a singh-pass power amplifier fed by the same master oscillator in parallel.

In one experiment, 6 CO, lasers were joined in the coupled resonator mode. With incoherent addition, the output would have been 6 times brighter than that of a single laser; with perfect coupling, the output would have been 36 times brighter. The experiment actually produced 23.4 times greater brightness. Experiments are under way to couple two l-kW, HF/DF lasers (with the coupled resonator approach) and to demonstrate MOPA operation of two HF laser amplifiers.[60]

Neutral Particle Beam.—Although accelerator technology is well established for ground-based physics experiments, much research, development, and testing are prerequisite to a judgment of the efficacy of a space-based particle beam weapon *system*. Key issues are presented in table 5-8.

[59] If added coherently, the beam brightness of "N" lasers would be "N^2" times the brightness of one laser. If the "N" lasers were not coherent, then the brightness of the combination would be the sum or "N" times the brightness of one laser.

'Actually, the MOPA experiment will utilize one amplifier with three separate optical cavities: one for the master oscillator and two for the amplifiers. (Source: SDI Laser Technology Office, Air Force Weapons Laboratory, unclassified briefing to OTA on Oct. 7, 1986.)

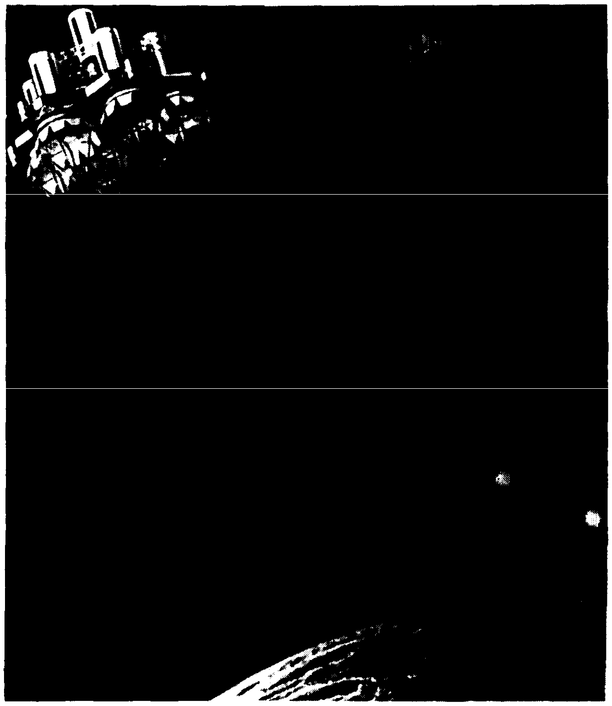


Photo *Credit: U.S. Department of Defense, Strategic Defense Initiative Organization*

Artist's conception of **a** phased array of lasers.—Since it may be impractical to build a single module space-based chemical laser of a size useful for ballistic missile defense, scientists and engineers are exploring the possibility of using several smaller laser modules that would be phase-locked to provide a single coherent beam. This technique could increase the attainable power density on a target by a factor of N* (instead of N for incoherent addition), where N is the number of modules.

Table 5-8.—Neutral Particle Beam Issues

- Major issues:
  - —Beam divergence: 50 times improvement required
  - –Weight reduction (50 to 100 tonnes projected)
  - —Kill assessment (or hit assessment)
- Other issues:
  - —Beam sensing and pointing
  - —Duty factor: 100 times improvement required
  - —Ion beam neutralization (50°/0 efficient)
  - —Space charge accumulation
  - —ASAT potential

SOURCE **Office of Technology Assessment, 1988**

The NPB ATS now at Los Alamos generates the necessary current (100 mA) for a NPB weapon, but at 20 to 40 times lower voltage, about 100 times lower duty cycle, and with about 50 times more beam divergence than would be needed for a space-based weapon. A continuous ion source with the *necessary* current levels has been operated at the Culham Laboratory in the United Kingdom with 30-s pulses, but not as yet coupled to an accelerator.

Researchers have planned a series of ground-based and space-based experiments to develop beams meeting NPB weapons specifications. It is possible that these experiments would encounter unknown phenomena such as beam instabilities or unexpected sources of increased beam divergence, but there are no known physics limitations that would preclude weapons applications.

High energy density at the accelerator would not be sufficient for a weapon. The beam would have to be parallel (or well-collimated, or have "low emittance" in accelerator parlance), to minimize beam spreading and maximize energy transmitted to the target. In general, higher energy beams have lower emittance, but some of the techniques used to increase beam current might increase emittance, possibly to the point where increased current would decrease energy coupled to the distant target. With high emittance, the NPB would be a short-range weapon, and more NPB weapons would be necessary to cover the battle space.

The divergence of existing, centimeter-diameter particle beams is on the order of tens of microradians; this divergence would have to be reduced by expanding the particle beam diameter up to the meter range.[61] This large beam would have to be steered toward the target with meter-size magnets. Full-scale magnetic optics have not been built or tested. However, one-third scale optics have been built by Los Alamos National Laboratory and successfully tested at Argonne National Laboratory on a 50 MeV beam line.

The weight of the NPB system would have to be reduced substantially for space-based operation. The RF power supply alone for a

[61] In theory, beam divergence decreases as the beam size is increased. In practice, the magnets needed to increase the beam diameter might add irregularities in transverse ion motion, which could contribute to increased beam divergence; not all of the theoretical gain in beam divergence would be achieved.

weapon-class NPB would weigh 160,000 kg (160 tonnes) if based on existing RF radar technology.[62] Using solid-state transistors and reducing the weight of other components might reduce RF weight about 22 tonnes.[63] One study concluded that a total NPB platform weight of 100 tonnes is "probably achievable."[64] Los Alamos scientists have estimated that the NPB platform weight for an "entry level," 100-MeV, NPB system could be 50 tonnes. Some day, if high-temperature, high-current superconductors became available, NPB weights might be reduced substantially.

Thermal management on a NPB satellite would be challenging. A NPB weapon might produce 40 MW of waste heat.[65] One proposal is to use liquid hydrogen to dispose of this heat. About 44 tonnes of hydrogen could cool the NPB for 500 s.[66] The expulsion of hydrogen gas would have to be controlled, since even a minute quantity of gas diffused in front of the weapon could ionize the beam, which would then be diverted by the Earth's magnetic field. Since the hydrogen gas would presumably have to be exhausted out opposing sides of the spacecraft to avoid net thrust, it might be difficult to keep minute quantities of gas out of the beam.

A state-of-the-art ion accelerator (the Ramped Gradient Drift Tube Linac) can raise beam energy about 4 MeV per meter of accelerator length. At this gradient rate, a 200-MeV beam would have to be over 50 m long. This accelerator could be folded, but extra bending magnets would increase weight and could reduce beam quality. The gradient could be increased, but if the ion beam energy were increased in a shorter length, then there would be more heating in the accelerator walls. This implies another system trade-off: reducing length in an attempt to cut weight might eventually reduce efficiency, which would dictate heavier RF power elements and more coolant. Again, future superconductors might ameliorate this problem.

The beam would have to be steered to intercept the target. A NPB would have two advantages over laser beams: the convenience of electronic steering and a lesser need for steering accuracy. Magnetic coils could steer negatively charged hydrogen ions before the extra electrons were stripped off. However, the angular motion of electronic steering would be limited: the entire accelerator would have to maneuver mechanically to aim the beam in the general direction of the target cluster. Like laser weapons, a NPB must have an agile optical sensor system to track targets. However, the divergence of the NPB is larger than most laser beams (microradians versus 20 to 50 nanoradians), so the beam steering need not be as precise.

On the other hand, a hydrogen beam could not be observed directly. The particle beam direction is detected in the laboratory by placing two wires in the beam. The first wire casts a shadow on the second wire placed downstream. By measuring the current induced in this downstream wire as the upstream wire is moved, the beam direction can be estimated to something like 6 microradian accuracy.

New techniques would be needed to sense the beam direction automatically with sufficient accuracy. One approach utilizes the fact that about 7 percent of the hydrogen atoms passing through a beam neutralization foil emerge in a "metastable" excited state: the electrons of these atoms acquire and maintain extra energy. Passing a laser through the beam can make these excited atoms emit light. The

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[62] The vacuum-tube (klystron) RF power supply for the PAVE PAWS radar system weighs approximately 2 g/W of power. A NPB weapon would emit an average power of 20 MW (2×10^7 watts), assuming 200 MeV beams at a current of 0.1 A. Assuming an overall efficiency of 25 percent (50 percent accelerator efficiency and 50 percent beam neutralization efficiency), the power supply would have to generate 80 MW average power, and would weigh 160 tonnes.

[63] This assumes that the RF power is generated with l-kW, commercial quality power transistors (80,000 transistors would be required for the hypothetical 80 MW supply). These transistors can only be operated at 1 percent duty factor. New cooling technology would have to be developed to operate at the 100 percent duty factor required for a NPB weapon. (See American Physical Society, op. cit., footnote 1, pp. 149 and 361.) The overall efficiency of these power supplies would be 40 percent.

[64] Ibid., p. 152.

[65] Assuming a 200-mA, 100-MeV beam, 50 percent neutralization efficiency, and 50 percent power generation efficiency.

[66] Assuming heat of vaporization only (450 J/g), and no temperature rise in the hydrogen. If the gas temperature were allowed to rise by 100° K, then the hydrogen mass could be reduced to about 14 tonnes.

magnitude of this fluorescence depends on the angle between the particle beam and the laser beam. Thus the NPB direction can be deduced and the beam boresighted to an appropriate optical tracking system. Laboratory tests have demonstrated 250 microradian accuracy, compared to the l-microradian accuracy necessary.[67] More recent tests at Argonne at 50 MeV have yielded better results.

The current technique to neutralize the hydrogen ions is to pass them through a thin foil or a gas cell. This process strips off, at most, 50 percent of the electrons, cutting the efficiency of the system in half and thus increasing its weight. A gas cell is not practical for space applications. A stripping foil must be extraordinarily thin (about .03 to.1 µm, or ten times less than the wavelength of visible light). In the proposed NPB weapon, a thin foil 1 m in diameter would have to cover the output beam. Clearly such a foil could not be self-supporting, but Los Alamos scientists have tested foils up to 25 cm in diameter that are supported on a fine wire grid. This grid obscures about 10 percent of the beam, but has survived initial tests in beams with average power close to operational levels.

Another beam neutralization concept is to use a powerful laser to remove the electrons-a technique that some assert may yield 90 percent efficiency. However, the laser stripping process would call for a 25 MW Nd:YAG laser (near weapon-level power itself), and it would eliminate the excited state hydrogen atoms needed for the laser beam sensing technique.[68]

Charged hydrogen ions that escaped neutralization might play havoc with an NPB satellite. The accumulation of charge might severely degrade weapon system performance in unforeseen ways, although NPB scientists are confident that this would not bean issue.[69] The Beam Experiment Aboard Rocket (BEAR) experiment with an ion source and the planned Integrated Space Experiment (ISE) should answer any remaaining doubts about space-charge accumulation.

Arcing or electrical breakdown that could short out highly charged components may also be a problem in space. Dust or metal particles generated in ground-based accelerators fall harmlessly to the ground. In space, floating particles could cause arcing by forming a conducting path between charged components.

Existing accelerators demand many hours of careful manual alignment before an experiment. Neutral particle beam weapons would have to operate automatically in space. Current plans call for the ATS accelerator at Los Alamos to be automated soon.

Kill assessment might be difficult for weak particle beam weapons. Damage deep inside the target might completely negate its function with no visible sign. The choices would be either to forgo kill confirmation or to increase NPB energy levels until observable damage were caused, possibly the triggering of the high-energy explosive on the RV. The current plan is to forgo kill confirmation per se, but to increase the NPB power level to assure electronic destruction. Sensors would determine that the particle beam had hit each target. Experiments are planned to assess whether UV light emissions would indicate that a particle beam had struck the surface of a target.

The planned (and now indefinitely postponed) ISE illustrates a point made in chapter 11 of this report: many BMD weapons would have ASAT capabilities long before they could destroy ballistic missiles or RVs. The ISE accelerator, if successful, would have ASAT lethality at close range, although for a limited duty cycle. Beam divergence might limit range, but it could probably destroy the electronics in existing satellites within 500 to 1,000 km.[70] Even though not aiming a beam

[67] See American Physical Society, op. cit., footnote 1, p, 172.
[68] See American Physical Society, op. cit., footnote 1, p. 148.
[69] One suggested that the neutralizing foil be thicker so that two electrons are stripped from some hydrogen ions, forming positive hydrogen ions (protons) to help neutralize the charge in the vicinity of the spacecraft.

[70] This experiment could have nearly BMD-level lethality, possibly raising issues with respect to the ABM Treaty. However, it would not have the necessary beam sensing and pointing or the computer software and hardware for a BMD weapon; SDIO considers the experiment to be treaty compliant.

at other than a target satellite, this experiment conceivably might disrupt nearby satellite electronics. Although this may not be serious (calculations indicate that it should not), there is enough uncertainty to cause ISE planners to ask whether they should wait until the Space Shuttle had landed before turning on the ISE.

X-ray Laser.—The nuclear bomb-driven x-ray laser is the least mature DE W technology. To date this program has consisted of theoretical and design work at Livermore National Laboratory and several feasibility demonstration experiments at the underground Nevada nuclear weapons test site. Actual x-ray generation technology may or may not reach suitable levels in the years ahead; currently the methods to convert this technology into a viable weapons system remain paper concepts.

POWER AND POWER CONDITIONING

The average electrical power consumed by some proposed BMD spacecraft during battle might be factors up to 100,000 over current satellite power levels. Most existing satellites are powered by large solar arrays that would be vulnerable to defense suppression attack. To provide sufficient *survivable* power for space applications, most BMD satellites would require either nuclear reactors, rocket engines coupled to electrical generators, or advanced fuel cells.

In addition to high average power, some proposed weapon satellites would demand high peak power: energy from the prime source, either a nuclear reactor or a rocket-driven turbo-alternator, would have to be stored and compressed into a train of very high current pulses. For example, a railgun might expend 500 MJ of energy in a 5-millisecond (ins) pulse, or 100 GW of peak power. This is about 1,000 times more than current pulse power supplies can deliver.

The following sections outline satellite power demands and the technologies that might satisfy them. While space systems would call for the primary advances, ground-based FELs would also depend on advances in pulsed-power supply technology. Some of the technology developed for space-borne neutral particle beam systems, such as RF power sources, might be applicable to FELs.

Space Power Requirements

Estimates of power needs of space-based BMD systems are summarized in table 5-9. Since most of these systems have not been designed, these estimates could change significantly: the table only indicates a possible range of power levels. Power is estimated for three modes of operation: base-level for general satellite housekeeping and continuous surveillance operations lasting many years; alert-level in response to a crisis, possibly leading to war;

Table 5-9.—Estimated Power Requirements for Space Assets (average power in kilowatts)

Mode of operation	Base	Alert	Burst (battle)
BSTS	4-1o	4-1o	4-1o
SSTS (IR)	5-15	5-15	15-50
Ladar	15-20	15-20	50-100
Ladar imager	15-20	15-20	100-500
Laser illumination	5-1o	5-1o	50-100
Doppler ladar	15-20	15-20	300-600
SBI carrier	2-30	4-50	1o-1oo
Chemical laser	50-100	100-150	100-200
Fighting mirror	10-50	10-50	20-100
NPB/SBFEL	20-120	1,000-10,000	100,000-500,000
EML (railgun)	20-120	1,000-10,000	200,000-5,000,000

SOURCE: Space Defense Initiative Organization, 1988.

and burst-mode for actual battle, which may last hundreds of seconds.

In addition to average-power and survivability perquisites, a space-based power system would have to be designed to avoid deleterious effects of:

- thrust from power-generating rockets upsetting aiming,
- torque due to rotating components,
- rocket effluent disrupting optics and beam propagation,
- vibration on sensors and beam steering,
- thermal gradients, and
- radiation from nuclear reactors.

Power systems would also have to operate reliably for long periods unattended in space.

Space Power Generation Technology

There are three generic sources of electrical power in space: solar energy, chemical energy, and nuclear energy.

Solar Energy

Solar panels have supplied power for most satellites. The sun produces about 1.3 kW of power on every square meter of solar array surface. An array of crystalline silicon cells converts the sun's energy into direct electrical current through the photovoltaic effect, with an efficiency of about 10 percent. Thus a l-m^2 panel of cells would produce about 130 watts of electricity, assuming that the panel were oriented perpendicular to the sun's rays. A 20-kW array, typical for a BMD sensor, would then have about 150 m^2–roughly, a 12-m by 12-m array. The Skylab solar array, the largest operated to date, produced about 8 kW. NASA has built, but not yet flown in space, a 25-kW experimental solar array designed to supply space station power.

The major disadvantage of solar arrays is that their large size makes them vulnerable to attack. Crystalline silicon photovoltaic cells are also vulnerable to natural and man-made radiation. One approach to reduce both vulnerabilities to some degree would be to concentrate the sun's rays with a focusing optical collector. The collector would still be vulnerable, but if the system efficiency could be improved, then the area of the collector would be smaller than equivalent ordinary solar cell arrays.

There are two other ways to convert the energy from solar collectors into electricity. One is to use solar thermal energy to drive a conventional thermodynamic heat engine. The other is to focus sunlight on more radiation-resistant and higher-efficiency photovoltaic cells such as gallium arsenide. Depending on the temperature of the working fluid in a thermodynamic heat engine cycle, efficiencies of 20 percent to 30 percent might be achieved. Gallum arsenide cells have shown up to 24 percent efficiency in the laboratory, so 20 percent efficiency in space may be reasonable. Thus, either technology could cut the required collector area in half compared to conventional solar cells, or 75 m^2 per 20-kW output. Neither approach has been tested in space, but NASA is pursuing both for future space applications.

Nuclear Energy

Nuclear energy has also been used in space. There are two types of nuclear energy sources: radioactive isotope generators that convert heat from radioactive decay to electricity, and nuclear fission reactors. Both have flown in space, but the radioactive isotope generator is more common.

Both radioactive decay and a controlled fission reaction produce heat as the intermediate energy form. This heat can be converted into electricity by static or dynamic means. A static power source produces electricity directly from heat without any moving parts, using either thermoelectric or thermionic converters. These converters generate direct current between two terminals as long as heat is supplied to the device. The efficiency and total practical power levels are low, but for applications of less than 500 W, the advantage of no moving parts makes a radioisotope thermoelectric generator (RTG) a primary candidate for small spacecraft.

To produce more than 500 W, a radioisotope source could be coupled to a dynamic heat engine. One dynamic isotope power system (DIPS) with 2 to 5 kW output has been ground-tested. This system weighs 215 kg. However, the U.S. production capacity for radioactive isotopes would limit the number of satellites that could be powered by DIPS.

BMD satellites needing more than 5 to 10 kW of power might carry a more powerful nuclear fission reactor. Static thermoelectric converters would still convert the heat to electricity. This is the approach proposed for the SP-100 space power program, the goal of which is to develop elements of a system to provide power over the range of 10 to 1,000 kW. The Departments of Defense and Energy and NASA are producing a reference design incorporating these elements to produce a 100-kW test reactor.[71] This is the major focus for the next generation of space power systems.

The SP-100 reactor, as currently designed, would use 360 kg of highly enriched uranium nitride fuel with liquid lithium cooling operating at 1,3500 K. This heat would be conducted to 200,000 to 300,000 individual thermoelectric elements which would produce 100 kW of electricity. The overall efficiency of the system would be about 4 percent, which would entail the disposal of 2.4 MW of waste heat. Large fins heated to 8000 K would radiate this heat into space.

The SP-100 program faces numerous challenges. In addition to being the hottest running reactor ever built, the SP-100 would be the first space system to:

- use uranium nitride fuel,
- be cooled by liquid lithium,
- use strong refractory metals to contain the primary coolant,
- have to start up with its coolant frozen,
- have two independent control mechanisms (for safety), and
- use electronic semiconductors under such intense heat and radiation stress.[72]

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The estimated mass of the SP-100 is 3,000 kg, or a specific mass of 30 kg/kW. Original plans called for building a ground-test prototype SP-100 based on the 100-kW design by 1991, with a flight test several years later. Subsequently a 300-kW design was considered which would have pushed initial hardware toward 1993, but current schedules are fluid due to uncertain funding.

To produce power levels in excess of a few hundred kW, one would have to take the next step in the evolution of space nuclear power systems: a nuclear reactor coupled through a dynamic heat engine to an electrical generator. In principle, large reactors in space could generate hundreds of MW, satisfying the most stressing BMD average power demands.

A "multimegawatt," or MMW, project has begun to study some of the fundamental issues raised by large reactors, including daunting engineering challenges such as high temperature waste heat disposal in space, safety in launch, operation, and decommissioning. These large nuclear systems might have to be

[71]Original SDIO plans called for designing a 300 KW system, but as of this writing the goal has been reduced to 100 KW.
[72]See Eliot Marshall, "DOE's Way-out Reactors," Science, 231:1359, March 21, 1986.

operated "open-cycle," requiring much "fuel" in the form of cooling gas to dispose of excess heat. At this writing the MMW project is in the conceptual phase with no well-defined research program. Multi-megawatt nuclear reactors in space would have to be considered a 20-to-30 year project.

In summary, space nuclear power systems would require extensive development to achieve reliable space operation at the 100-300 kW level by the mid-to-late 1990s. Given current engineering and budget uncertainties, development of megawatt-class nuclear power systems for space cannot be projected until well into the 21st century.

Chemical Energy

Satellites frequently employ chemical energy in the form of batteries, fuel cells, and turbogenerators. Batteries would be too heavy for most BMD applications, except possibly for pop-up systems with very short engagement times. Fuel cells, which derive their power by combining, e.g., hydrogen and oxygen, are under active consideration for driving the accelerators of NPB weapons.

For the short bursts of MMW power needed by some BMD weapons, an electrical generator driven by a rocket engine (e.g., burning liquid hydrogen and liquid oxygen) might be the only available technology in the foreseeable future. The Space Shuttle main engine (SSME) develops about 10 GW of flow power, which could generate 5 GW of electrical energy if it could be coupled to a turboalternator. Alternatively, rocket exhaust could, in principle, be converted to electricity by magnetohydrodynamics (MHD).

The engineering challenges of using rocket engines to produce electrical power on board a BMD satellite are posed not only by the generator itself, but by its effects on other components such as sensors, electronics, and weapons. Two counter-rotating and counter-thrusting rockets would probably be essential to cancel torque and thrust. Even then, sensors and weapons-aiming devices would have to be isolated from vibration. Similarly, the effluent from the rocket engines must not interfere with sensors or weapon beam propagation, and electrical noise must not interfere with communication or data processing electronics.

It might be necessary to place rocket engines and power generators on separate platforms hundreds or a few thousands of meters away to achieve the necessary isolation, transmitting power by cable or microwaves. This method, however, would raise vulnerability issues, presenting to the adversary an additional target and a vulnerable umbilical cord.

Power Conditioning

Power conditioning is matching the electrical characteristics of a power source with those required by the load. A generator might produce a continuous flow of electrical current, but a load, such as railgun firing, would require a series of very high-current pulses. Power conditioning equipment would convert the continuous flow into pulses.

In some cases the projected power conditioning device requirements exceed existing capabilities by two or three orders of magnitude, even for ground-based experiments. In many areas, no space-qualified hardware exists at any power level. Pulsed power technology development efforts are underway in capacitive and inductive energy storage, closing and opening switches, transformers, RF sources, AC-DC converters, and ultra high-voltage techniques and components.

Particle accelerators that drive the FEL and the NPB use RF power. Railgun requirements would present the greatest challenge: very short (millisecond) pulses of current several times a second. Many electrical components would have to be developed to produce the proper current pulses for a railgun.

A homopolar generator combined with an inductor and opening switch is now the primary candidate for the generation of very short pulses. A homopolar generator is a rotating machine that stores kinetic energy in a rotating armature. At the time of railgun firing, brushes would fall unto the armature, extracting much of its energy in a fraction of a second. This would result in a sudden jerk in the torque of the generator, which would disturb a spacecraft unless compensated by a balanced homopolar generator rotating in the opposite direction.

The brushes would also wear out, which raises questions about the durability of a railgun with high repetition rates. Very fast switches would be essential. These switches would have to be light enough to move rapidly, but heavy enough to handle the extraordinarily high currents.

Researchers at the University of Texas have investigated one advanced modification to the homopolar generator. They have replaced brushes and switches with inductive switches in a "compulsator," a generator which produces a string of pulses. By replacing non-current carrying iron with graphite-epoxy composites, these compulsators could be much lighter than the homopolar generators.

While space applications drive power development requirements, emerging ground-based defensive systems would also stress existing power sources. Ground-based BMD elements might require diesel and turbine driven electric generators and MHD generators for mobile applications. A fixed-site system such as the FEL might draw on the commercial utility grid, dedicated power plants, or superconducting magnetic energy storage (SMES). The electrical utility grid could meet peacetime housekeeping power needs and could keep a storage system charged, but, due to its extreme vulnerability to precursor attack, could not be relied on to supply power during a battle. Therefore, a site-secure MMW power system would probably be necessary.

Superconducting magnetic energy storage is a prime candidate for ground-based energy storage; an SMES system would be a large, underground superconducting coil with continuous current flow. The science of SMES is well established, but engineering development remains.

Recent discoveries of high-temperature superconductors could have an impact on future power supplies and pulse conditioning systems. Given the likely initial cost of manufacturing exotic superconducting materials and the probable limits on total current, their first applications will probably be in smaller devices such as electronics, computers, and sensor systems. But if:

- scientists could synthesize high temperature superconducting materials able to carry very large currents; and
- engineers could develop techniques to manufacture those materials on a large scale suitable for large magnetic coils, RF power generators, accelerator cavity walls, the rails of electromagnetic launchers, etc.;

then superconductors could substantially reduce the power demand. Efficiency of the power source and power conditioning networks could also be improved. High temperature superconductors would be particularly attractive in space, where relatively cold temperatures can be maintained by radiation cooling.

COMMUNICATION TECHNOLOGY

Communication would be the nervous system of any BMD system. A phase-one defense would include hundreds of space-based components, separated by thousands of kilometers, for boost and post-boost interception. A second-phase BMD system would include many tens of sensors in high orbits and hundreds to several thousands of weapons platforms in low-Earth orbits. "

Three fundamental communication paths would link these space assets: ground to space, space to space, and space to ground. Ground command centers would at least initiate the battle; they would also receive updates on equipment status and sensor data in peacetime and as the battle developed.

The attributes of an effective communication system would include:

- adequate bandwidth and range,
- reliability,
- tolerance of component damage,
- security from interception or take-over,
- tolerance of nuclear effects, and
- jam- or spoof-resistance.

The bandwidths, or frequency space available, from links in the millimeter-wave bands would be adequate for most near-term BMD functions. The most demanding element would be the boost surveillance and tracking system (BSTS) satellite, with perhaps a l-million-bit-per-second data rate. Second-phase elements such as a space surveillance and tracking system (SSTS) sensor satellite might operate at much higher rates, up to 20 million bits per second, while battle management might take 50 or more million bits per second of information flow. Various additional data for synchronization signals would have to be communicated. Transmission bandwidths might have to be very large-perhaps 1-10 gigahertz (GHz) –to reduce the chances of jamming.

The communication system must be durable and survivable even if some nodes fail due to natural or enemy action. Redundant links in a coupled network might assure that messages and data got through even if some satellites were destroyed. Tying together a vast BMD space network would be challenging, especially given that the satellites in low-Earth orbit would constantly change relative positions.

One key issue for BMD communications is jamming by a determined adversary. Successfully disrupting communications would completely negate a BMD system that relied on sensors and command and control nodes separated from weapons platforms by tens of thousands of km. Jammers could be developed, deployed, and even operated in peacetime with little risk of stimulating hostile counteraction.

Space-to-ground communication links would be particularly vulnerable. Ground-based, ship-based or airborne high-power jammers might block the flow of information to satellites. In wartime, nuclear explosions could disrupt the propagation of RF waves. Ground-based receivers would also be susceptible to direct attack. Even space-based communications would be susceptible to jamming.

Recently there have been two primary SDI candidates for BMD communication links in space: laser links and 60-GHz links. A 60-GHz system once seemed to promise a more jam-resistant channel for space-to-space communications, since the atmosphere would absorb enough 60-GHz energy to reduce the threat of ground-based jammers. Recent analyses, however, indicate that space and air-based jammers may limit the effectiveness of 60-GHz links.

60-GHz Communication Links

The operating frequencies of space communication systems have been steadily increasing. For example, the Milstar communications satellite will use the extremely high frequency (EHF) band with a 44-GHz ground-to-space uplink and a 20-GHz downlink. These high frequencies allow very wide bandwidth (1 GHz in the case of Milstar) for high data transmission rates, but also for more secure communications through wide-band-modulation and frequency-hopping anti-jamming techniques.

For space-to-space links, BMD designers are considering even higher frequencies-around 60 GHz. This band includes many oxygen absorption lines. It would be very difficult for ground-based jammers to interfere with 60-GHz communications between, for example, a BSTS early warning satellite and SBI CVs: oxygen in the atmosphere would absorb the jamming energy.

Pre-positioned jammer satellites, or possibly rocket-borne jammers launched with an attack, might still interfere with 60-GHz channels. The main beam of radiation from a 60-GHz transmitter is relatively narrow, making it difficult for an adversary to blind the system from the main lobe: the enemy jammer transmitter would have to be located very close to the BMD satellite broadcasting its message. But a 60-GHz receiver would also pick up some energy from the "sidelobes" and even some from the opposite side of the receiver (the "backlobes"). While a receiver may be 10,000 to 100,000 times less sensitive to energy from these sidelobes than from the main lobe, it must be extremely sensitive to pickup signals from a low-Earth orbit satellite tens of thousands of km away.

At high-Earth orbit, a near-by jammer with only a few hundred watts of power could overwhelm a much more powerful 60-GHz system on a sensor satellite. This neighbor might masquerade as an ordinary communications satellite in peacetime. In wartime, it could aim its antenna at the BSTS and jam the channel. The countermeasure would be to station the BSTS out of standard communications satellite orbits.

Laser Communication Links

The low-power diode laser offers the possibility of extremely wideband, highly directional, and, therefore, very jam-proof communications. The MIT Lincoln Laboratory has designed a 220 megabit-per-second (Mbs) communication link that would need just 30 milliwatts of laser power from a gallium aluminum arsenide (GaAIAs) light emitting diode (LED) to reach across the diameter of the geosynchronous orbit (about 84,000 km). The receiver, using heterodyne detection,[73] could pull in a signal of just 10 picowatts (10^{-11} W) power. A 20-cm mirror on the transmitter would direct the laser beam to an intended receiver.

The high directionality of narrow laser beams also complicates operation. A wide-angle antenna could flood the receiver area with signal, even sending the same message to many receivers in the area at one time. A narrow laser beam must be carefully aimed at each satellite. This would require mechanical mirrors or other beam-steering optics, as well as software to keep track of all friendly satellites and to guide the optical beam to the right satellite. The lifetime of a laser source and an agile optical system may be relatively short for the first few generations of laser communication systems.

A laser communication system, as presently designed, would require up to eight minutes to establish a heterodyne link between a transmitter and a receiver. Plans call for reducing this acquisition time to one minute. With a very narrow laser beam, even minute motions of the transmitter platform could cause a momentary loss of coupling, forcing a delay to reacquire the signal.

While laser links might provide jam-proof communications between space-based assets of a BMD system, laser communications to the ground would have to overcome weather limitations. One approach would use multiple receivers dispersed to assure one or more clear weather sites at all times. Alternatively, one could envisage an airborne relay station, particularly in time of crisis.

[73] The common "heterodyne" radio receiver includes a local oscillator which generates a frequency that is combined or "mixed" with the incoming radio signaL This process of "mixing" the local oscillator signal with the received signal improves the ability to detect a weak signal buried in noise, and reduces interference. A laser heterodyne receiver would include its own laser source, which would be "mixed" at the surface of a light detector with the weak light signal from a distant laser transmitter.

SPACE TRANSPORTATION

Reasonable extensions of current U.S. space transportation capability might launch the tens of sensor satellites envisaged by some BMD architectures, but entirely new space launch capabilities would be necessary to lift several hundred to over one thousand carrier vehicles and their cargoes of thousands to tens of thousands of kinetic kill missiles into space in a reasonable period of time. Therefore space launch capability would have to evolve along with phase-one and phase-two weapon systems to assure the United States—and to persuade the Soviet Union-that a defense-dominated world would be feasible and enduring.

Space Transportation Requirements

Space-based interceptors and their carrier satellites would dominate initial space deployment weights. Assuming that a phase-one deployment would include a few hundred CV\sS and a few thousand SBIs based on the "state-of-the-art" rockets described above, then total launch weight requirements might be in the range of 1 million to 2 million kg.

The range of weights estimated by SD I system architects for a more advanced phase varied from 7.2 to 18.6 million kg. The large range of weight estimates reflects differences in architectures, and particularly differences in survivability measures. Several contractors indicated that survivability measures—such as shielding, decoys, proliferation, and fuel for maneuvering-would increase weight by a factor of about three. One could infer that the heavier designs might be more survivable.

Additional space transportation would be required over time for servicing, refueling, or replacement of failed components. One unresolved issue is how best to maintain this fleet of orbiting battle stations: by originally including redundant components such as interceptor missiles on each satellite, by complete replacement of defective satellites, by on-orbit servicing, or by some combination of the above. One contractor estimated, for example, that it would take 35 interceptor missiles on each battle station to assure 20 live missiles after 10 years, with the attrition due entirely to natural component failures.

Soviet countermeasures might drive up weight requirements substantially in later years. Increased Soviet ICBM deployments might be countered with more SB I platforms. Defense suppression threats such as direct-ascent ASATs might be countered in part by proliferation of SBI battle stations or by other heavy countermeasures. Advanced decoys dispersed during the post-boost phase of missile flight might require some type of interactive discrimination system in space. Reduced Soviet booster burn times would eventually impel a shift to DE W. Deploying these countermeasures would necessitate additional space transportation capability. Directed-energy weapon components in particular would probably be very heavy. The range of SDI system architects' estimates for some far-term systems was from 40 million to 80 million kg.

Space Transportation Alternatives

There seem to be two fundamental options for lifting the postulated BMD hardware into space: use derivatives of existing space transportation systems; or design, test, and build anew generation space transportation system. The first option might be very costly; the second might postpone substantial space-based BMD deployment into the 21st century.

Some BMD advocates outside the SDIO have suggested that existing United States space launch systems might be adequate for an initial spacebased BMD deployment in the early 1990s. But the existing United States space launch capability is limited in vehicle inventory, payload capacity per launch, cost, launch rate, and launching facilities. As shown in table 5-10, today's total inventory of U.S. rockets could lift about 0.27 million kg into low-Earth orbit (180 km) at the inclination angle of the launch site (28.50 for the Kennedy Space Center in Florida) .74

The bulk of early SBI deployments would have to be launched into near-polar orbits from Vandenberg AFB, which would now only be possible for the 6 remaining Titan 34D vehicles with a combined lift capacity of 75,000 kg.

"Missile launch capacity is usually specified in terms of the payload which can be lifted into direct East-West flight at an altitude of 180 km, which produces an orbit inclined at the latitude of the launch point. Extra propellant is required to lift the payload to higher inclinations or to higher altitudes. Proposed BMD weapons systems would require higher inclinations (700 to850, and higher altitudes (600 to 1,000 km), which translates into lower payload capacity.

This would correspond to about 6 percent of the initial phase-one BMD space deployment requirements. Some have suggested refurbishing Titan-IIs, which have been retired from the ICBM fleet. If all 69 Titan-IIs were refurbished, then the United States could lift another 130,000 kg into polar orbit, or another 11 percent of the near-term BMD needs.

The rate of missile launch might also be limited by the existing space transportation infrastructure. Launching one Shuttle now takes a minimum of 580 hours at the Kennedy Space Center (and might take about 800 hours at Vandenberg AFB[75]), limiting potential launches to one per month or less from each complex. After the Shuttle accident, NASA estimated that 12 to 16 flights per year would be reasonable. Clearly 16 launches per year would not be sufficient for BMD deployment.[76]

Several aerospace companies have proposed building launch vehicles with increased lift capacity to meet SDI, DoD, and civilian space transportation demands. Many of these vehicles would be derived from various Shuttle or Titan predecessors, such as the Titan-4, included in table 5-10. Twenty-three Titan-4s will be built by 1988, but these have only marginally increased lift capacity. A major increase in lift capacity to the 40,000 to 50,000 kg range would be required for an effective space-based BMD system. Even for a phase-one system, far more would be needed by the mid-1990s. Both SDIO and Air Force officials have called for anew space transportation system that is not a derivative of existing technology.

Four aerospace companies analyzed various space transportation options under joint Air Force/NASA/SDIO direction. The Space Transportation Architecture Study (STAS) compared manned v. unmanned vehicles, horizontal v. vertical takeoff, single v. 2-stage rockets, and various combinations of reusable v. expendable components.[77] The &r Force, after reviewing the initial STAS work, appears to be leaning toward a decision that the BMD deployment should use an unmanned, expendable, 2-stage heavy-lift launch vehicle (now called the ALS or advanced launch system).[78]

[75]Completion of the Vandenberg Shuttle launch site SLC-6 has been postponed until 1992.

[76]Assuming 16 Shuttle launches per year with 9,000 kg payload to low polar orbit, it would take between 8 to 12 years to deploy a phase-one BMD system and 48 to 125 years to deploy a phase-two system weighing 7 to 18 million kilograms.

[77]The Space Transportation Architecture Study (STAS) was a joint Air Force/NASA/SDIO study on future space transportation systems. The Air Force Systems Division contracted with Rockwell and Boeing, while NASA employed General Dynamics and Martin Marietta to analyze U.S. civilian and military space requirements and possible alternatives to satisfy them.

[78]The name HLLV (heavy lift launch vehicle) was changed to ALS in April 1987.

Table 5-10.—Current U.S. Space Launch Inventory[a]

	Payload per vehicle (thousands of kg)			
	Inventory quantity	LEO (180 km)	Polar (180 km)	Geo
Shuttle	3	25	15	Centaur-G:4.5 IUS: 2.3
Titan 34D		15,3	12.5	IUS: 1.8
Titan-4[b]	(23)	17.7	14.5	Centaur-G:4.6 IUS: 2.4
Titan 11-SLV	(13)[c]	3.6	1.9	
Delta		2.9		
Delta (MLV)	(7)	4		1.5
Atlas	13	6		
scout	21	.26		
(ALS)[d]	?	(50-70)	(40-55)	

[a]Parentheses indicate future systems.
[b]The Titan-4 or the Complementary Expendable Launch Vehicle (CELV) is the latest in the line Of Titan missile configurations; 23 have been ordered.
[c]The Titan II-SLVs are being refurbished from the ICBM inventory. The first Titan-n may be available by 1989. An additional 56 Titan II could be refurbished from the retired ICBM fleet.
[d]The Advanced Launch System is proposed to deploy the bulk of the BMD space components.

SOURCE: Office of Technology Assessment, 1988.

An interim STAS study suggested that such a vehicle would have to evolve to a partially reusable system to meet SDIO cost reduction goals. The STAS contractors projected that development of a heavy-lift unmanned vehicle would require about 12 years, although at least one aerospace company estimates that an ALS could be developed in 6 years. If the original 12-year estimate is correct, significant space deployment of a BMD system could not begin until the turn of the century even if the weapon systems were ready earlier. If the 6-year estimate were correct, then initial deployment could begin by 1994.

To deploy space-based assets earlier, SDIO has suggested a two-tier level program: build part of an ALS by the mid-1990s, but design this system to evolve into the long-range system by the year 2000. The initial system would include some of the advanced features of the heavy-lift launch vehicle concepts outlined by STAS, but would not have a fly-back booster and would not meet the SDIO cost goals of $300 to $600 per kilogram. The interim goal would be to reduce the current costs of $3,000-$6,000 per kilogram to $1,000-$2,000. Building a space transportation system while trying to meet these two goals simultaneously could be risky. Compromises might be required either to meet the early deployment date or to meet the long-term cost and launch rate goals.

The estimated launch rate for a fully developed ALS vehicle is about once per month per launch complex.[79] Assuming a 40,000-kg payload to useful BMD orbits, then between 30 and 45 successful flights would be required for a phase-one BMD deployment and from 180 to 460 flights for a much larger second phase. Allocating 5 years to deploy the latter system, the United States would need to build three to eight new launch facilities.[80]

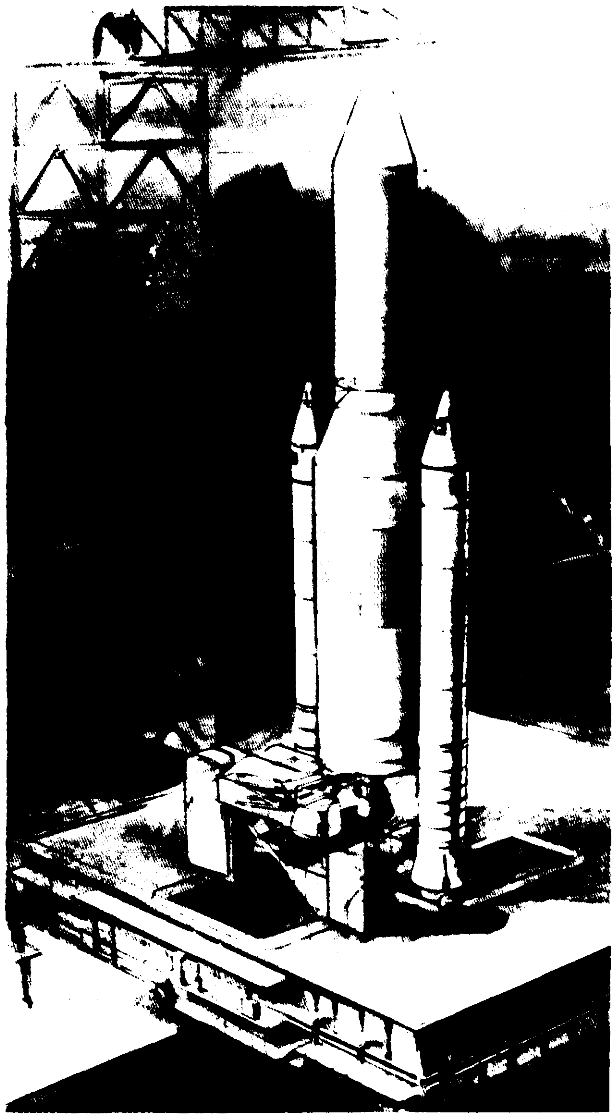


Photo credit: U.S. Department of Defense, Strategic Defense Initiative Organization

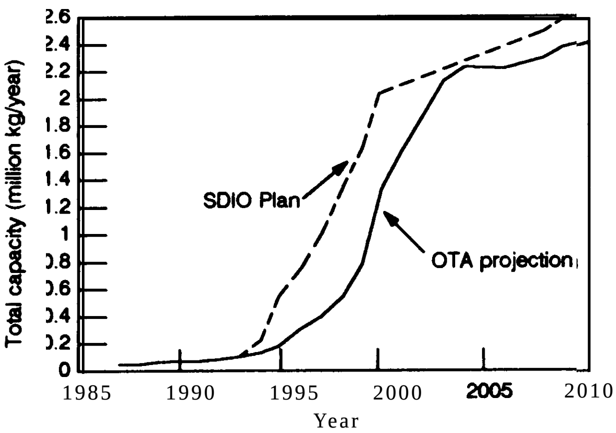
Advanced launch system (ALS).—Large-scale deployment of space-based interceptors (SBI) or other weapons in space will require a dramatic expansion of US. space-launch capabilities. Various proposals, including a Shuttle-derived, unmanned launch vehicle such as this have been under consideration by the Air Force, NASA, and the SDIO.

Figure 5-13 presents one very optimistic sce nario which might lead to space launch facilities adequate for proposed second-phase BMD

[79] The current maximum launch rate for Titans is three per year from each pad, which might be increased to five per year. Further increases are unlikely because the Titans are assembled on-site. This is one of the reasons an entirely new space launch system would be needed to meet the SDI launch rates.

[80] The United States now has four launch pads for Titan-class boosters, two on the east coast and two on the west coast. One west coast pad is being modified to handle the CELV. Since SBIs would have to be launched from Vandenberg to reach near-polar orbits, all early deployments would have to be from one pad. The estimated time to build a new launch pad complex is 7 to 10 years,

Figure 5-13a. —Annual Space Launch Capacity
(near polar orbits at 800 km)



This is one possible scenario to achieve the 2 million kg per year space launch capability into near-polar orbits required for an intermediate ballistic missile defense system. This system could conceivably reach this goal by the year 2003, assuming that three new launch pads were built at Vandenberg AFB, and the proposed Heavy Lift Launch Vehicle (HLLV)/Advanced Launch System (ALS) could be developed, flight tested, and ready for initial service with 30,000 kg lift capacity by 1994. This would be 5 years ahead of the schedule initially suggested by the Space Transportation Architecture Study (STAS). The HLLV is further assumed to evolve into a 44,000 kg capability by the year 2000, without any engineering delays. The SDIO launch goals as of early 1987 are shown for comparison.

SOURCE: Office of Technology Assessment, 1988.

Table 5-il.—Space Transportation

Vehicle capacity to 600 km, high inclination:
(thousands of kilograms)

CELV (Titan-4)	115
Titan 34D	
Earty HLLV	30 (1995-2000)
Final HLLV	44 (2000+)

Launch pads:	4-East: (34D/CEL)	SLC-6 (HLLV)	(HLLV)	(HLLV)	(HLLV)	Total annual launch Capacity (M kg)
	Number of launches per year					
Year						
1965	3					003
1986	3					003
1987	3					003
1966	3					003
1989	4					005
1990	4					005
1991	5					0.06
1992	5					0.06
1993	6					007
1994	6	1				010
1995	7	2				014
1996	7	6				026
1977	6	6	1			036
1998	6	10	2	2		051
1999	6	12	4	4	2	075
2000	6	12	6	6	4	132
2001	6	12	8	8	6	1.59
2002	6	12	10	10	6	165
2000	6	12	12	12	10	212
2004	6	12	12	12	12	220
2005	6	12	12	12	12	2.20
2006	8	12	12	12	12	220
2007		12	13	12	12	225
2008	8	12	13	13	12	229
2009	6	12	14	13	13	236
2010	6	12	14	14	13	242

Tabular data for figure 3-13a.

SOURCE: Office of Technology Assessment, 1988.

systems by 2000-2005. This scenario assumes that the SDIO two-level space transportation development approach would be successful: an interim ALS vehicle, with a 30,000 kg capability to near-polar orbits, would be available by 1994; a more advanced ALS would come online in 2000 with 44,000 kg capacity. Three new launch pads would be built (although there is no room for three new pads at Vandenberg AFB, the only existing site in the contiguous United States with near-polar orbit capability).

Assuming approval to proceed with the new launch system in 1988, the first flights of the new ALS would begin in 1994, using the refurbished SLC-6 launchpad at Vandenberg, built originally for the Space Shuttle. The three new pads would become operational in 1997,1998, and 1999. Flights would be phased in at each site, increasing up to 12 flights per year per pad. With these assumptions, the SDIO goal of 2 to 2.5 million kg per year could be achieved by 2003.

If the United States were to operate 10 launch facilities, each with one ALS launch per month, then it would take about 10 years to orbit the 50 million kg estimated for a far-term, third-phase system.[81] If political or strategic considerations (such as transition stability) would not allow as long as 10 years to deploy, then the United States would have perhaps three choices:

1. develop another new vehicle with lift capacity above 50,000 kg to 800-km, high inclination orbits;
2. build and operate more than ten ALS launch facilities simultaneously; or

[81] The 50 million kg assumes the low end of the 40 to 80 million kg estimated above for phase three with space-based lasers. A successful ground-based laser system could reduce this estimate by about 15 million kg, or 25 to 65 million kg for a total phase-three constellation.

3. improve launch operations to reduce turn-around time below 30 days per pad.

The country would have to expand booster manufacturing capacity to meet this demand for up to 120 launches per year. Historically, Titan production lines completed up to 20 missiles per year, and Martin Marietta has estimated that it could easily produce 14 of the Titan class per year with existing facilities.[82]

Space Transportation Cost Reduction

Identifying 42 technologies related to space transportation, the STAS listed several where research might lead to reduced operating costs (it emphasized the first three as offering especially high leverage for cost reduction):

- lightweight materials,
- expert systems and automated programming to cut software costs,
- better organization,
- reducing dry weights substantially,
- better ground facilities,
- higher performance engines,
- fault-tolerant avionics,
- reusability of major components, and
- better mating of spacecraft to launch vehicle for reduced ground costs.

[82] This would include 5 CELVS, 6 Titan 11s, and 3 Titan 34Ds.

The operating (as opposed to life-cycle) costs of space transportation are currently estimated at $3,300 to $6,000 per kilogram of payload to low-Earth orbit, and $22,000 to $60,000 per kilogram to geosynchronous orbit. At that rate, it would cost $24 billion to $200 billion to launch a phase-two BMD system, and $140 billion to $450 billion for a responsive phase-three deployment, based on the constellation weights estimated by various SDIO system architects. The SDIO has set a goal of reducing launch operating costs by a factor of 10.

Operating costs are estimated at about one third of the total *life-cycle* costs of a space transportation system. Based on current operating costs, total life-cycle costs for transporting a phase-two BMD system into space might be $72 billion to $600 billion; for phase three, the costs might range from $420 billion to $1.35 trillion. Reaching the goal of reducing operating costs by a factor of 10 would reduce life-cycle costs for space transportation by only 30 percent. Assuming that this percentage would be valid for a new space transportation system, and assuming a 10 to 1 reduction in operating costs only, then the total life-cycle costs for space transportation might be $50 billion to $420 billion for a phase-two deployment and $290 billion to $900 billion for a phase-three deployment. Clearly the other kinds of costs for space transportation would have to be reduced along with the operating costs.

CONCLUSIONS

Weapon Technology Conclusions

Phase One

Kinetic Energy Weapons.—KEWs (or else the kinds of nuclear-armed missiles developed for BMD in the 1960s) would most likely be the only BMD weapons available for deployment in this century and possibly the first decade of the 21st century. Several varieties of non-nuclear, hit-to-kill KEW form the backbone of most near- and intermediate-term SDI architecture proposals. Considering the steady evolution of rockets and "smart weapon" homing sensors used in previous military systems, it seems likely that these KEWs could have a high probability of being able to destroy individual targets typical of the current Soviet ICBM force by the early to mid-1990s. The key unresolved issue is whether a robust, survivable, integrated system could be designed, built, tested, and deployed to intercept—in the face of likely countermeasures—a sizeable fraction of evolving Soviet nuclear weapons.

Space-Based Interceptors.—SBIs deployed in the mid to late 1990s could probably destroy some Soviet ICBMs in their boost phase. The key issue is whether the weight of the SBI projectiles could be reduced before Soviet booster burn times could be shortened, given that existing SS-24 and SS-25 boosters would already stress projected SBI constellations. The probability of post-boost vehicle (PBV) kills is lower due to the smaller PBV size and IR signal, but SBIs might still achieve some success against current PBVs by the mid to late 1990s.

Exe-atmospheric Reentry Interceptor System.—The ERIS, which has evolved from previous missiles, could probably be built by the early to mid-1990s to attack objects in late mid-course. The key unknown is the method of tracking and discriminating RVs from decoys. Existing radar sensors are highly vulnerable, the SSTS space-based IR sensor probably would not be available until the late 1990s to early 2000s, and the AOS airborne sensor would have limited endurance and range. This would leave either new radars or some type of pop-up, rocket-borne IR probe, which have apparently received little development effort until recently. Given the uncertainty in sensors suitable for the ERIS system, its role would probably be confined to very late mid-course interceptions and it might have limited BMD effectiveness until the late 1990s.

Phase Two

High Endo-atmospheric Defense Interceptor. —The HEDI could probably be brought to operational status as soon as the mid-1990s. To overcome the unique HEDI window heating problem, the HEDI on-board homing IR sensor needs more development than its ERIS cousin. But the HEDI system does not depend on long-range sensors to achieve its mission within the atmosphere. The HEDI could probably provide some local area defense of hardened targets by the mid-1990s against non-MaRVed RVs.[83] HEDI performance against MaRVed RVs appears questionable.

SBIs against Reentry Vehicles.-The probability that SBIs would kill RVs in the mid-course is low until the next century, given the difficulty in detecting and tracking many small, cool RVs in the presence of decoys, and given uncertainties in the SSTS sensor and battle management programs.

Phase Three

Directed-Energy Weapons. -It is unlikely that any DEW system could be highly effective before 2010 to 2015 at the earliest. No directed energy weapon is within a factor of 10,000 of the brightness necessary to destroy responsively designed Soviet nuclear weapons. (OTA has not had the opportunity to review recent SDIO suggestions for "entry level" DEWS of more modest capability. SDIO contends that effective space-based lasers of one to two orders of magnitude less than that needed for a responsive threat could be developed much sooner.) At least another decade of research would likely be needed to support a decision whether any DEW could form the basis for an affordable and highly effective ballistic missile defense. Further, it is likely to take at least another decade to manufacture, test, and launch the large number of satellite battle stations necessary for highly effective BMD. Thus, barring dramatic changes in weapon and space launch development and procurement practices, a highly effective DEW system is unlikely before 2010 to 2015 at the earliest.

Neutral Particle Beam.-The NPB, under development initially as an interactive discriminator, is the most promising mid-course DEW.[84] Shielding RVs against penetrating particle beams, as opposed to lasers, appears prohibitive for energies above 200-MeV. Although laboratory neutral particle beams are still about 10,000 times less bright than that needed for sure electronics kills of RVs in space, the necessary scaling in power and reduction in beam divergence appears feasible, if challenging.

[83] "MaRV" refers to maneuvering reentry vehicles, or RVs which can change their course after reentering the atmosphere to improve accuracy or to avoid defensive interceptors.

[84] The NPB would have virtually no boost phase capability against advanced "responsive" boosters since particle beams cannot penetrate below about 150 kilometers altitude.

However, as discussed in chapter 4 under the topic of NPB interactive discrimination, it is unlikely that engineering issues could be resolved before the late 1990s, which would most likely postpone deployment and effective system operation to at least 2010-2015.

Free Electron Laser.—The free electron laser (FEL) is one of the more promising BMD DEW weapon candidates. The FEL is in the research phase, with several outstanding physics issues and many engineering issues to be resolved. Even if powerful lasers could be built, the high power optics to rapidly and accurately steer laser beams from one target to the next could limit system performance. Although the basic system concept for an FEL weapon is well developed, it is too early to predict BMD performance with any certainty.

Chemical Laser.—There are too many uncertainties to project BMD performance for the chemically pumped hydrogen fluoride (HF) laser. The HF laser has been demonstrated at relatively high power levels on the ground, although still 100,000 times less bright than that needed for BMD against a responsive threat. Scaling to weapons-level brightness would require coherent combination of large laser beams, which remains a fundamental issue. This, coupled with the relatively long wavelength (2.8 micron region), make the HF laser less attractive for advanced BMD than the FEL.

Electromagnetic Launcher.—There are too many uncertainties in the EML or railgun program to project any significant BMD capabilities at this time.

Space Power Conclusions

Phase One

Power Requirements.—Nuclear power would be required for most BMD spacecraft, both to provide the necessary power levels for stationkeeping, and to avoid the vulnerability of large solar panels or solar collectors.

Dynamic Isotope Power System.–The DIPS, which has been ground-tested in the 2 to 5 kW range, should be adequate and available by the mid to late 1990s, in time for early BSTS-type sensors.

Phase Two

Nuclear Reactors.—Adequate space power may not be available for SSTS or weapon platforms with ladars before the year 2000. For BMD satellites that require much more than 10 kW of power the SP-100 nuclear reactor/thermoelectric technology would have to be developed. This is a high-risk technology, with space-qualified hardware not expected before the late 1990s to early 2000s.

Phase Three

Chemical Power.—Chemically driven energy sources (liquid oxygen and liquid hydrogen driving turbogenerators or fuel cells) could probably be available for burst powers of MW up to GW to drive weapons for hundreds of seconds by 2000-2005.

Power for Electromagnetic Launchers. -High-current pulse generators for electromagnetic launchers (EML) would require extensive development and engineering, and would most likely delay any EML deployments well into the 21st century.

High-Temperature Superconductors.–Research on high-temperature superconductors suggests exciting possibilities in terms of reducing the space power requirements and improving power generation and conditioning efficiencies. At this stage of laboratory discovery, however, it is too early to predict whether or when practical, high current superconductors could affect BMD systems.

Space Communications Conclusion

Laser communications may be needed for space-to-space and ground-to-space links to overcome the vulnerability of 60-GHz links to jamming from nearby satellites. Wide-band laser communications should be feasible by the mid-1990s, but the engineering for an agile beam steering system would be challenging.

Space Transportation Conclusions

Phase One

Mid-1990s Deployments.—Extrapolating reasonable extensions of existing space transportation facilities suggests that a limited-effectiveness, phase-one BMD system begun in the mid-1990s could not be fully deployed in fewer than 8 years.[85] Assuming that the hardware could be built to start deployment in 1994, the system would not be fully deployed until 2002. A more ambitious launcher-development program and a high degree of success in bringing payload weights down might shorten that period.

Phase Two

New Space Transportation System.—A fully new space transportation system would be required to lift the space assets of a "phase-two" BMD system. This system would have to include a vehicle with heavier lift capability (40,000 to 50,000 kg v. 5,000 kg for the Tita.n-4), faster launch rates (12 per year v. 3 per year per pad), and more launch pads (4 v. 1).

Optimistic Assumptions.—Even under very optimistic assumptions,[86] the new space transportation system would be unlikely to reach the necessary annual lift requirements for a large-scale, second-phase BMD until 2000-2005, with full phase-two deployment completed in the 2008-2014 period.

Phase Three

Ultimate DEW Systems.–It might take 20 to 35 years of continuous launches to fully deploy far-term, phase-three BMD space assets designed to counter with very high effectiveness an advanced, "responsive," Soviet missile threat. This estimate assumes deployment of the proposed ALS space transportation system and the kind of advanced space-based laser constellation suggested by SD I system architects. A set of ground-based laser installations could reduce the space launch deployment time estimate to 12-25 years.

[85] This assumes that two launch pads at Vandenberg AFB, 4-East and the SLC-6 pad intended for the Shuttle, are modified to handle the new Titan-4 complementary expendable launch vehicle (CELV), and the launch rates are increased from three Titans per year per pad up to six per year.

[86] This assumes that the SDIO bifurcated goal is met: a revolutionary space transportation system with 10 times lower cost is developed in 12 years, while a near-term component of that system yields a working vehicle of reduced capability by 1994.