Appendix - G

Commentary on the APS Report on Boost-Phase Missile Defense

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Abstract: A brief review and summary on the recently published "Report of the American Physical Society Study Group on Boost Phase Intercept Systems for National Missile Defense" as related to space weaponization is presented. Comments on some of the findings and conclusions are also discussed.

Introduction

A brief review, summary, and extension of the recently published "Report of the American Physical Society (APS) Study Group on 'Boost Phase Intercept Systems for National Missile Defense'" (APS, 2003) to the Federation of American Scientists (FAS) "Report of the Advisory Committee on Space Weaponization " is presented. It is the purpose of this review to provide a link between the APS study group and the FAS advisory panel publication in order to better interpret some of the issues involved in the national missile defense (NMD). Also, in this commentary, policy issues, not addressed in the non-political APS study, are briefly discussed.

The grounding or the rationale for NMD rests upon postulated external threats to the United States (U.S.). NMD as putatively and currently envisaged does not mean to provide retaliatory cover for a first strike capability against a modern industrial nation with a substantial arsenal of nuclear, biological, and chemical (NBC) weapons. Such a nation can, in response to the development of an extensive NMD effort, simply choose to produce enough war- heads, decoys, and missiles to significantly overwhelm a missile defense shield. Instead, NMD has the intent of protecting against a limited (asymmetric) attack from irresponsibly aggressive groups operating within a limited geographic region; it can also act to some extent as a means for theater missile defense in a limited conventional (symmetric) conflict. Establishing a NMD will not counter other terrorist threats to the U.S. and its allies from weapons of mass destruction (WMDs) that, for example, can be smuggled into a country and released. Indeed, if one denies the Intercontinental Ballistic Missile (ICBM) route to an adversary, re-directed efforts are likely to take place, wherever possible. Bringing WMDs to the soft-target-rich U.S. by alternative methods to destroy or disrupt infrastructure from within is a possibility that cannot be ignored. Also, terrorist activities could concentrate on overseas U.S. and allied targets, carrying out cyber attacks to destroy or disrupt parts of the financial and security communication links, or carry out other vicious aggressions that kill, injure, and psychologically menace a population. Nonetheless, although a limited ICBM threat is certainly not the only possible option to attack the U.S., it is thought by some to be a real option that can cause immense damage and must be neutralized to as great an extent as possible. This is underscored by the proliferation of longer range ballistic and cruise missiles via legitimate modern industrial powers to some minor resource-rich countries or extremist states that may then trans-ship the ordinance to suspected rogues or terrorists, for example. It is now thought that a significant number of "rogue states" and "non-state-entities" are in the process of attempting to acquire ballistic missiles (BMs) with a variety of WMD warheads, from simple volumetric to the sophisticated nuclear devices.

An overriding concern regarding effective deployment of a NMD system is the argument that missile defenses are inherently leaky. This raises the question as to why any U.S. President would risk depending on leaky missile defenses as a safeguard against any irresponsibly aggressive rogue state. There are at least three reasons. First, there is the "its better than nothing " invocation. Second, of penultimate utility, it may deter a potential aggressor with a very limited ICBM arsenal from considering an attack against the U.S. Third, and perhaps of ultimate utility, it provides the nation with a NMD the ability for a greater freedom of action to neutralize WMD sites of a postulated rogue state or its entire regime through a pre-emptive strike without fear of a significant missile retaliation. To a large extent, within the context of a pre-emptive strike, NMD substantially limits options of a marginal regime to use missiles against the U.S. (Coyle 2004).

Neutralizing the ICBM threat in its early stage boost-phase interception (BPI) both from Earth's surface and from space has been an area of discussion and it is the subject of this commentary based on the APS "Study on Boost Phase Intercept Systems" [APS, 2003]. Related to the APS study is the FAS "Report of the Advisory Panel on the Weaponization of Space," [FAS, 2004] within which this report appears.

Boost Phase Interception

Among the options for the NMD strategy is BPI. As the name implies, it is the capability of destroying or substantially disabling attacking BMs within the first few minutes of flight, while the missiles are in their propulsion state and boosters still have a radiant exhaust plume. With BPI the understanding is that the BMs are relatively easy to detect and target. An advantage of destroying ICBMs in the boost stage is that they are under great mechanical stress and not likely to have deployed decoys or sub-munitions. Almost any direct hit on the boosters would be lethal and have a high expectation of registering a kill. The downside is that there is only a limited time to intercept and destroy ICBMs before booster burnout; after that time, munitions deployment can occur and the target(s) are considerably smaller, stronger, and less luminous.

As a service to the U.S. and its allies, the Federation of American Scientists study on "Space Weaponization" is analyzing the use of space-based weapons for NMD. In a related report, another independent scientific group of experts, the American Physical Society, has analyzed in some technical detail the advantages and disadvantages of BPI. The recent report of the APS on "Boost Phase Intercept Systems for National Missile Defense provides a technical framework to evaluate the architecture and sub-systems required to achieve a successful BPI from ground and sea platforms as well as from the air and space. The interception vectors primarily considered were mechanical impact (mechanical kill vehicle) and coherent (laser) radiation. Warhead sub-munitions and "homing overlay" extensions methods to increase the destructive radius received brief discussion in terms of enhancing the lethality of the kill vehicle. Lethality confirmation remains a big problem unless one carries out a reliable warhead kill assessment in the presence of countermeasures and debris. To some extent, the APS study considered space-based weapons (SBW) as a means of BPI; hence, some overlap exists between the APS and FAS studies on this topic. In addition, much of the background material in the APS study is relevant to the FAS study. This is helpful because it provides different perspectives on the same issues that this FAS study is addressing.

Report of the American Physical Society (APS) on "Boost Phase Intercept Systems for National Missile Defense"

The recently released far-reaching report of the APS on "Boost Phase Intercept Systems for National Missile Defense" extensively covers the dynamic performance and systems aspects of BPI. This is an important educational and policy contribution to the debate on missile defense and provides an excellent background for this FAS study. The APS study group is commended for providing a document that provides considerable insight into the NMD debate. The aims of both the APS and FAS reports are to provide clear and analytical frameworks to outline the technical arguments on space-based weapons and BPI in a credible and impartial manner that would be helpful to the public at large and to policy makers in particular. Since there is an overlap of topics, specifically the use of SBW to effect BPI, parties may discuss an interpretation of those parts of the APS study relating to SBW in the light of the some of the interpretations derived from this FAS study. Additionally, because NMD is so important and many interested parties may have the interest but not the time or technical background to critically review the lengthy APS study, this commentary highlights some main arguments and conclusions of the APS study while also introducing interpretations.

Key Issues

A great deal of material in the APS study of BPI carefully outlines the key kinematic and system parameters required for analysis of the BPI. The report contains two parts. The first and much shorter part (Volume I) is an extended executive summary with conclusions regarding boost-phase missile defense. This part focuses on the geometry and kinematics of the interactions. Volume II of this report reviews the technical requirements to hit an accelerating missile, supporting analysis for hit-to-kill engagements, and an analysis for airborne laser (ABL) engagements. There are several tables and numerous figures in the APS report that provide a quantitative framework ror ascertaining the requirements of range, velocity, and available time for a BPI. The general approach uses systems analysis, and is well done. A broad review of available detection, sensor, and related guidance technologies and kill assessments provide a clear and understandable introduction to these subjects at a very basic level. However, high-speed (>5 km/s) materials interactions are not included. This is understandable because high-speed impact analysis depends on materials properties interactions and equations-of-state under very high pressures and temperatures within short times frames, which is quite complex and not particularly relevant to the objectives of this study. Discussions concerning interceptor design, space platforms, and surveillance configurations appear in adequate detail. Recent versions of the interceptor kill vehicle and some sensor configurations (upgrades) do not appear in the report and may not be available for a variety of reasons. Nevertheless, this omission does not significantly compromise the report's integrity or conclusions. To aid the non-specialist, the report provides four glossaries and four technical appendices. Overall, this is an excellent report with a great deal of technical information that can serve as a significant part of the scientific background for the missile defense debate.

The key issues in the APS study are summarized in **dark print.** Comments and/or interpretations by the author appear in *italics.*

1. **To hit an ICBM with an interceptor, given the inherently unpredictable acceleration in the boost phase, the kill vehicle would have to be very agile, fast, and carry a sufficient amount of fuel. These interceptors must also use very large rockets.**

Since their defendable areas are relatively small the current blocks of SM-2 and SM-3 Aegis class missiles do not appear to be generally capable of such in-terceptions unless the target engagement geometry is extremely favorable to an interception. Essentially, Aegis missile cruisers are best at defending themselves.

2. **The time allocated from launch to ICBM interception before burnout is ~3 minutes for a solid propellant and 4 minutes for a liquid propellant boosters. With such little time available for BPI, interceptors must achieve maximum velocity much faster (~ 4 times) than the ICBMs. Interceptors undergoing these enormous g-forces have never been constructed.**

Concerning the timing for liquid propellant boosters, Table 1 provides a time line derived from the APS report. The burnout velocity for a putative interceptor rocket is estimated to be about 7.5 km/s, although interceptor velocities can cover a wide range of values.

3. The boost phase interception range for rocket interceptors must be within 400 to 1,000 km of the intercept point.

With current technology, an overtake-and-kill at 1,000 km appears somewhat unrealistic. For the ABL to be optimally effective, the stationing radius must be within 300 to 600 km.

4. A damaged or destroyed BMW would (roughly) follow its ballistic trajectory and fall to Earth, possibly contaminating populated areas. It is thought that if the BMW munitions were destroyed the problem would be eliminated.

This statement may not be generally applicable because it depends on the overall physics of the interception interaction as well as the type of munitions and their arming and detonation mechanisms. For example, radioactive debris (fallout) could be a serious problem under many circumstances. However, it may be possible to consume or deactivate a chemical or biological warhead in the interception process. In the BPI, the larger and more luminous target is the booster, not the BMW, so the warhead munitions may not necessarily be destroyed if it is not directly hit or if the explosion of the booster does not sufficiently damage the BMW.

5. BPI fired from platforms in (low Earth) orbit in principle could defend the U.S. against ICBMs launched from anywhere on Earth. While the coverage would not be constrained by geography, SBI would have the same time constraints and engagement uncertainties as terrestrial-based interceptors.

As opposed to BPI, for optimal engagement scenarios in the post-BPI, the SBI engagement geometry provides considerably more time for interception. There would be different constraints on targeting, range and other factors depending on the deployment of the SBI, permitting use of a smaller interceptor rocket if it could actually be developed. A very important consideration to the disadvantage of the SBI is the much reduced size of the target that is now a much cooler BMW and not an ICBM with a hot booster plume.

6. **Assuming the ABL laser works as planned, it is limited by the distance its beam can propagate through the atmosphere and remain focused. The effective range is estimated to be 600 km against a LP ICBM and about 300 against a SP ICBM. Countermeasures to the ABL include applying ablative coatings, rotating the ICBM to distribute the heat, multiple missile launches with decoys, and attacking the ABL.**

The assumption that an ABL will work as planned, i.e. adequate intensity on-target, is enormously optimistic. The effective range of 600 km is also quite optimistic. ABL may be better suited as an anti-satellite (ASAT) or theater defense weapon for tactical or, if limited to cloudless skies at a medium altitude range, cruise missile interception. However, for theater defense the ABL might have to be even closer to the target and therefore more vulnerable itself as a target. In any case, experiments and field-testing results from subsystems of the ABL, such as the tracking and beacon illumination lasers should answer many questions about laser interception of missiles.

7. **Countermeasures to BPI by rockets include, for example, rocket propelled decoys, jammers, multiple launches, and evasive maneuvers in the propulsion mode could overwhelm the interceptor's capabilities.**

These countermeasures are more likely to be effectively fielded by an industrially sophisticated adversary, rather than from the postulated (minor) players.

It is believed by some that the optimal advantage of having space-based weapons (SBW) would be to use them for a post-BPI or a mid-course interception. Overall, BPI, whether ground or space launched, has several obstacles to overcome before one can consider it as a viable missile defense option. Many of these obstacles are discussed in the findings of the APS study group, as are some advantages of the mid-course intercept (MCI) option.

Findings of the APS Study Group

A summary of the findings of the APS study in its own words appear below in smaller print.

1. Intercepting missiles during their boost phase presents major challenges not faced by midcourse-intercept systems, which allow 20 to 25 minutes to observe, track, and intercept while BPI allows from 170 to 240 s. Boost phase trajectories are somewhat unpredictable but mid-course trajectories are considered inherently predictable.

2. The effective ranges of BPI hit to kill are limited by the short duration of the ICBM boost phase. The ABL is limited primarily by the distance its beam can propagate through the atmosphere while remaining focused and to a lesser extent of its power.

3. The large and unpredictable variations of the ICBM boost phase trajectories and the short engagement times available for engaging them drive the requirements for any BPI kinetic kill interceptor.

4. The only way a BPI can assure that lethal warheads will not strike a defended area is to disable the attacking missile before the earliest time it can achieve the velocity needed to carry its munitions to that area, because the defense does not know the particular target. This time is uncertain because the missile may fly at various trajectories and execute a variety of maneuvers to manage its energy or evade the defense.

5. A robust boost-phase defense against ICBMs would require modern space-based sensors to detect launches and provide initial tracking information needed to launch interceptors. Even so, it would take at least 45 to 65 s to detect the and establish a track of its trajectory accurate enough to launch an interceptor. Such sensors would be needed to provide continually updated tracking information to the interceptors as they fly to the target. A system such as the high altitude Space-Based infrared system (SBIRS-High) now under development could perform these functions if the boost-phase defense requirement is included in its design. (Note that the existing Defense Support Program (DSP) could provide launch detection and initial tracking, but it would take 30 s longer to obtain a firing solution than a system such as SB IRS-High).

6. While boost-phase defense against slow-burning liquid-propellant ICBMs not employing countermeasures appears technically feasible for some geographic scenarios, the much shorter burn times typical of solid-propellant ICBMs using even 40-year old technology call into question the fundamental feasibility of any boost phase intercept of such threats at useful ranges, no matter where or how the interceptors are based, even with the most optimistic assumptions about detection and track times.

7. According to U.S. intelligence estimates, North Korea and Iran could develop or acquire solid propellant ICBMs within the next 10 to 15 years. Boost-phase defenses are not able to defend against solid propellant ICBMs risk being obsolete when deployed.

8. The time constraints imposed on any boost-phase defense system by the short duration of ICBM boost phases would pose significant real-time decision issues. [The decision to fire interceptors would have to be almost automatic]. Dense cloud cover above 7 km is not likely to prevent detection of a rocket launch.

9. Despite the variations and uncertainties inherent in the boost-phase trajectories of ICBMs, our analysis indicates that a kill vehicle incorporating current sensor and guidance technology could home on ICBMs in powered flight with precision compatible with direct kill requirements, assuming the kill vehicle's booster could place it on a trajectory that would take it within homing range of the ICBM. The kill vehicle would also have to meet certain critical performance criteria.

10. Although a successful intercept would prevent munitions from reaching their target, live nuclear, chemical, or biological munitions could fall on populated areas short of the target, in the United States or in other countries. This problem of shortfall is inherent in boost-phase defense.

11. Airborne interceptors offer some unique advantages for boost-phase defense, but they also have significant limitations in defending against ICBMs. They could be deployed more quickly than land- or sea-based interceptors in response to new threats, but several backup aircraft equipped with interceptors, as well as refueling aircraft and defensive air cover, would be required for every airborne interceptor aircraft on station.

12. A constellation of space-based interceptors (SBIs) could, in principle, overcome the geographic limitations of terrestrial-based interceptors and intercept ICBMs launched from much of Earth's surface. However, they would be subject to range and time constraints similar to those that constrain terrestrial-based systems. Consequently achieving reasonable coverage between the latitudes of 45 degrees North and South would come at a very high cost.

13. Although boost-phase missile defense systems using hit-to-kill interceptors could avoid some of the countermeasures to midcourse intercept that have been proposed, there are effective countermeasures to such boost-phase systems. Many of them have been demonstrated in past U.S. programs for other purposes.

14. The Airborne Laser (ABL) has been designed to intercept theater ballistic missiles and is scheduled to achieve initial operational capability in about 10 years. It could offer some capability for intercepting ICBMs, but would have less range than large ground-based hit-to-kill interceptors. ABL aircraft could be rapidly deployed, but several ABL aircraft, as well as tanker support aircraft and defensive air cover, would be required to maintain one ABL aircraft continuously on station. While the ABL has some self-defense capability, without supporting tactical air cover ABL aircraft would be vulnerable to attack by enemy aircraft or surface-to-air missiles.

15. Few of the components that would be required for early deployment (i.e. within 5 years) of a boost-phase defense currently exist. Moreover, we see no means for deploying an effective boost-phase defense against ICBMs within 19 years. Several key components are lacking and are unlikely to be developed in much less than a decade.

16. Much of the public discussion on missile defense has focused on ICBM attacks, but the threat posed by existing short- or medium-range tactical ballistic missiles launched from ships or other platforms positioned off the U.S. coasts is more immediate. It appears that a missile similar to the existing U.S. Navy Aegis Standard Missile 2 could engage short or medium range ballistic missiles launched from sea platforms without significant modification, provided that the Aegis ship is within a few tens of kilometers of the launch platform.

17. In our [APS Study Group] view, there are many issues for a boost-phase intercept system that requires further study before the true capabilities and deployment timeliness of boost-phase missile defense can be determined.

Concluding Remarks from the APS Study Group

The upshot from the APS study is that boost phase technologies studied are potentially capable of defending the U.S. against LP ICBMs at "certain ranges of interest," at least in the absence of countermeasures. However, when considering all the factors, few of the required boost-phase defense system components may be available for the foreseeable future to defend the nation against even first-generation solid propellant ICBMs. Given that any aggressor would fully understand the implications of the above comments, it is not likely that they would deploy a WMD warhead to a system that can easily be identified in origin, invite immediate retaliation, and is likely to be defeated. If the asymmetric aggressor decides to confront the U.S. or its allies with a limited ICBM threat, which is generally a non-optimal use of these weapons, they are likely to use a SP ICBM, preferably with a fast burn booster and launched well inland far away from guided missile cruisers and other proximate countermeasures. Some implications of these remarks are expanded upon in the comments below.

Comments on Some Specific Findings of the APS Study Group

Overall, the author agrees with all the above findings of the APS study group and makes the following clarifications on items 7, 11, 12, and 16.

Item 7: Based on past patterns of global military technology transfer, if they sustain the current levels of technical armaments growth, it is possble that North Korea and perhaps even Iran will be able to obtain solid propellant ICBMs within 5 to 10 years. But the future level of aggressive motivations by different players cannot be predicted.

Item 10: Target shortfall is likely to be more of a problem for terminal rather than boost or midcourse interception of missiles.

Item 11: ABL is a completely new type of untested weapons system with some major technical obstacles that the U.S. must overcome. It must test the simulated studies of the ABL under realistic combat conditions before it can rely on its BPI ability to destroy real ICBMs. This uncertainty must be factored into the NMD system effectiveness. The large amounts of flammable, pressurized liquid (oxygen-iodine) chemicals contained within the laser gain medium presents a potential danger to the air crew and also limits its maneuverability and survivability under attack.

Item 12: Time allowances for SBI would be substantially larger if interception takes place in the post-BPI or in MCI. That is, for the mid-course interception phase, there would be 20 to 25 minutes available for detection through interception. Whereas for a ground based interceptor, at best, less than only 4 minutes are available for a BPI. Considerably more time is available for ground -based terminal interception. This longer interception time would provide advantages for interceptor design and guidance. With the judicious strategic deployment of SBI platform constellations based on effective intelligence and innovative orbital deployment, interception range requirements may be optimized.

Item 16: Interception range, velocity and acceleration capabilities of the updated Standard Missile 3 (SM-3), not directly mentioned in this APS study, has better interception capabilities than the SM-2 [Robinson, 2002]. In general, however, the Aegis class missiles were not designed for and are not generally effective for BPI [Postal, 2003], and, as already mentioned, are best at defending themselves and small adjacent volumes. For both BPI and MCI an effective sea-based missile would have to be roughly twice as fast as existing navy missiles today.

A principal consideration of the APS study is the time-frame estimations of the interception ranges required for ICBM BPI. The study discussed current BPI technologies ranging from ground- or ship-based kinetic energy missiles or kinetic energy kill vehicles (KKV) to space based interceptors. Also considered is the use of the airborne laser (ABL). The primary strategic objective of the ABL system is to destroy ICBMs in the boost phase. Since this is a new and highly innovative project that is introducing several new technological subsystems, no demonstration of the overall systems effectiveness can or does exists. And until it is shown to be effective in realistic ICBM interception scenarios considerable uncertainty will remain as to whether the ABL can achieve its strategic objectives. The ABL technology may be effective as a weapon against theater ballistic missiles or as an anti-satellite (ASAT) weapon (see next section). Although in terms of ASAT capabilities, demonstrations suggest that a missile launched from a fighter aircraft can be an effective tactical ASAT weapon, it appears that the ABL would far exceed other methods in this role.

The APS study stressed current technologies and so parameters for a space-based laser (weapon) could not realistically enter into the NMD calculus simply because, apparently, it does not yet exist. For an excellent, but dated, review of possibilities of directed energy weapons, consult the "Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons [Rev. Mod. Phys., 1987].

Theoretically, the APS panel found that under certain circumstances BPI weapons can be effective against liquid propellant (LP) ICBMs because they take a longer time to achieve burnout (~240 s) than the solid propellant (SP) ICBMs (~170 s). It is clear from the systems analysis, reaction times, and geographical considerations that the BPI timeline is very close for neutralizing even the LP ICBMs. For the interceptor systems considered in the study, BPI of SP ICBMs would not be effective. The intelligence community believes that by the time one deploys the first generation BPI interceptors, deployment of the SP ICBMs will also occur. From this perspective, the APS study does not appear to support the efficacy of the BPI option to these emerging nuclear-ICBM threats.

Timeline for BPI

A conclusion that may be directly drawn from the time-line described in table 1 of this analysis suggests the initial objective must be to identify a predator as soon as possible and immediately obtain a firing solution, initiate a launch, develop tracking, and cause an interception. For a BPI to be seriously considered, an interceptor should be tested that can exceed these requirements. It appears that the sensor and communication technologies will be possible to develop, but developing a ground-based interceptor missile that can achieve a burnout velocity of 10 km/s will likely require, because of the limitations imposed by the rocket equation, a very high mass ratio which dictates a much larger rocket than the current

Aegis. Table 1 shows an extrac- tion from the APSstudy on the kinematics of BPI for a time-line for SP and LP ICBMs.

Table 1

Timeline for Boost-Phase Defense against SP and LP ICBMs Launched from Iran against East Coast cities of the U.S.

Propellant values given in seconds. (The ICBM has a head start of 75 to 95 s on the interceptor in addition to the fact that the interceptor has to travel at an angle to overtake and intercept the ICBM.)

Trajectory Stage	Solid Propellant ICBM	Liquid Propellant ICBM
ICBM Launch	0	0
ICBM Detection....................	30	45
Interceptor Firing Solution.........	45	65
Total Elapsed Time Before Decision for Interceptor Launch...	75	95
Available time for interception 5 s before burnout*	165	235

* Assumes the boost phase for the SP and LP ICBMs are 170 and 240 s respectively.

Technical Considerations

If the clock starts at 0 s when the ICBM is launched, the following estimated time sequences are initiated: detection (30-45 s), evaluation, firing solution, and interceptor launch (45-65 s), and firing after a 30 s interval. If an interception decision is made immediately upon obtaining a firing solution, this allows (120-170 s) for interception 5 s before burnout (the former and latter values refer to a solid and liquid propellant ICBMs respectively). But this is risky. If the interceptors are launched after an additional 30s evaluation interval, only 90-140 s are available for interception. The specification of highly constrained time lines is critical because the short reaction and interception times are at the crux of the BPI problem that will dominate the interceptor design as well as effect the command decision (see below) to intercept. These time lines assume minimal interference from decoys, trajectory variation maneuvers, deploying payloads during the boost phase, and other countermeasures that could either delay the launch decision or confuse interceptors to the extent it would consume additional time while the ICBM completes its boost phase.

Given these stringent time parameters, it is clear that a key to successful BPI is designing a missile to intercept a boosting ICBM. The interceptor must have a very high fly-out velocity and quickly reach terminal velocity while sustaining very high g forces. The interceptor must have a very high sustained speed and acceleration with an accurate guidance system that can execute an optimal firing solution to intercept the ICBM within the remaining ~3 to 4 minutes available in the boost phase after launch. Because of the time constraints on overtaking and destroying an ICBM in a BPI at a range of 300 to 600 km, the (ground-launched) interceptors would require a burnout velocity of ~8-10 km/s within less than 50s from launch, depending on the detection and decision times. This places an enormous g-force and thermal burden on the rocket and its terminal guidance (IR tracking system) and control system. This overall system would most likely be very large and robust unless one can achieve a design breakthrough.

Another potential technical problem, for example, is the ability of the space-based (infrared) sensors to distinguish between the missile and the hot gas envelope generated from the booster plume. The APS report did not extensively treat issues concerned with lethality and system effectiveness in terms of defining engagement baskets, accuracy, and kill verification. These issues represent a major problem for missile defense especially when decoys are involved that attract the attention of interceptors and absorb a significant share of the ICBM countermeasures. If a kill on a real ICBM warhead can be confirmed it frees up reserve interceptors and secondary defense assets to target additional incoming ICBMs.

Command Considerations

A potential command problem with the timeline constraints is that there is no way that the required timelines be operationally achieved unless the decision was delegated deep within the system to personnel actively engaged in the defensive operation. Clear decision criteria must be established so that there is a minimum of uncertainty or debate. This implies a substantial risk. Such an approach may be feasible when there are ongoing operations, heightened alert, or a crisis level that permits a sufficiently wide latitude for decisions, deployments, and warnings such as for an pre-emptive attack or an expected retaliation. However, such a command structure response appears to be incompatible within a scenario involving a rogue state suddenly launching ICBMs.

The ABL is mounted within a highly modified version of a Boeing commercial 747-400 series aircraft. The weapons system consists of a megawatt-class chemical oxygen iodine laser whose primary mission is to kill ballistic missiles in the boost phase of flight. In its deployment role as an airborne ant-ballistics missile laser platform it is expected to loiter at an altitude of about 12 km at a relatively low velocity. Given the short time window for a fast-burn SP ICBM to achieve maximum velocity and shed its boosters, the ABL must be close to its interception position even before the ICBM is launched. Operationally, the ABL is expected to detect missiles shortly after cloud break and provide near real-time launch warning to adjacent forces. The ABL is also expected to quickly and precisely locate the missile launch point. The primary scientific question regarding the ABL system effectiveness is whether a sufficient amount of energy can overcome the effects of atmospheric absorption and dispersion and deliver to a given surface area a fluence (J/m2) per unit time and intensity (J/m2-s) sufficient to disable the missile. An important technical question is whether the sensor, battle-management, and targeting software can be made to work together effectively to place the required fluence on the target.

The author suggests that the airborne laser (ABL) as currently configured with the multi-element COIL (continuous wave or CW) laser emitting coherent radiation at 1.315 micrometers could have some defensive capabilities against LP ICBMs, but it would be less effective against SP ICBMs that are far more heat resistant. Because the ABL is a blend of many new and sophisticated electro-optical systems, such as its laser beam control system which has yet to be fully assessed, it is generally agreed that the ABL will have many highly challenging technical objectives to overcome. If it were not for the dramatic advancements in adaptive optics (AO) to limit beam spread from (turbulence induced) atmospheric index of refraction variations, the ABL would not be at all feasible [Tyson, 1991].

COIL operates at an atomic iodine laser transition. An excited state of molecular oxygen generated by chemical reactions between chlorine gas and an aqueous mixture of hydrogen peroxide and potassium peroxide. Molecular iodine is then injected and mixed with the gas flow. Some of the energy in the oxygen is used to dissociate and excite the iodine. The gas flow is accelerated to a supersonic velocity in an expansion nozzle to create the laser gain region. Coherent radiation is extracted from a laser cavity positioned transverse to the gas flow (U. S. Air Force 2004).

At the current time it appears that several technical problems require addressing for (high-power) laser weapons to be effective in general. In the particular case of the COIL laser that operates from an accelerating, twisting, vibrating airborne platform, it is important to solve the serious challenges for beam stability. Additionally, it is important to optimize the Strehl ratio, which measures laser beam (transverse mode) quality and intensity for the resonator output on a target [Remo, 1984]. A related application of innovative work on anisoplanatic effects [Sutton, 2003] that can limit CW energy deposited on the target has achieved success; applying this success to the defense technologies of energy missiles would be quite beneficial. Nonetheless, the low energy conversion efficiency (and high thermal output) of lasers remains a (fundamental) limiting barrier to significantly better airborne laser performance.

It is the opinion of some that pulsed lasers, as opposed to CW, can inflict more damage to many surfaces per joule of energy expended. However, the effectiveness of a pulsed laser depends on the peak intensity, pulse shape, laser wavelength, and energy deposited per pulse. Designing such a high powered systems will be difficult. for many reasons among which includes the burden on the resonator and focusing optics. Currently, the technology of beam correction for high power pulsed lasers is far behind that for CW lasers. Perhaps ultra short pulse (=4 nanoseconds) and ultra intense (=1015 Watts/cm2) lasers may be adoptable to defense technologies (SAUUL 2002). For these reasons, the issue of using lasers to defeat a target is problematical and depends on the above parameters, the laser type, as well as on the target material properties. The overall operational design goals for the COIL ABL is a CW beam output power of ~ 3 MW, an (on-target) beam quality of 1.2 times the diffraction limit, and an alignment and pointing capability of 100 nanorad. These are very ambitious goals within the context of the proposed laser optical system.

In light of the above operational design goals it should be mentioned that the following problems specific to the COIL ABL include the following.

1. Low laser energy and high heat output per kilogram and per Joule of energy expended,

2. Aircraft vibrations and bending can introduce perturbations to the optical cavity system that will affect the resonator and guidance optics and therefore the Strehl ratio and beam jitter on the target,

3. Intrinsically unstable and flammable massive reservoirs of pressurized mildly toxic chemicals are onboard the aircraft; the chemistry of mixed alkali hydroxides (sodium, lithium, potassium hydroxide, and peroxide) is not thoroughly understood

4. Ability of the aircraft to maneuver with the massive cargo,

5. Enhanced atmospheric distortions at shallow incident angles to the atmospheric surface layers can introduce ducting and related beam spread; there is a limit to what AO can achieve,

6. Aircraft vulnerability to attack and a need for virtually complete air superiority,

7. Precursor rockets or aircraft can spread fine particles in the atmosphere which would be suspended and scatter the laser beam,

8. Cirrus cloud cover could effectively shield a threatening missile from the ABL beam for a significant time,

9. Multiple ABLs may be needed to defend against multiple missile launches, and

10. Ineffectiveness against a rotating and ablation protected target. Even under ideal circumstances, the laser beam dwell-time should be greater than 5 s, and preferably at ~20 s.

However, there are advantages to the COIL ABL system that include:

1. Development of laser beam tracking methodologies from a moving platform as performed by the tracking illumination laser (TILL),

2. Development of target illumination technologies from a moving platform as carried out by the beacon illumination laser (BILL) which illuminates a small spot on the target,

3. Demonstration of almost instantaneous interaction time at laser beam speed to target which substantially reduces interaction time constraints and increases target interaction time for BPI,

4. Multiple targeting capabilities with priorities targeting the most threatening missiles first,

5. Use of adaptive optics to compensate for atmospheric distortion by conjugating the output laser beam,

6. Development of integrated battlefield management surveillance sensors, and

7. Demonstration of integrated battle implementation and beam control systems.

8. Development of improved methods and means to process iodine gases with potential commercial spin-offs.

9. Solutions towards mitigating the beam degrading effects on the physical optics from very high energy density interactions.

10. May provide a systems platform for a new generation of ultra-fast, ultra-intense lasers.

It is possible to configure the ABL to be an ideal selective anti-satellite weapon, especially for blinding optical systems and damaging thin-skinned space assets while minimizing orbital debris. Maintaining an ABL presence against a surprise attack will require a substantial logistical effort requiring several ABL aircraft. Nevertheless, for selective theater missile coverage over a short period of time the ABL could be more effective within a geographical region. If the ABL is able to achieve some airborne testing under simulated combat results it will be very helpful in making decisions for developing future CW and pulsed laser weapons systems. For this reason, it may be a worthwhile endeavor as a research and development project for transportable high-powered laser beams.

In summary, as opposed to CW laser output systems such as the COIL, equivalent pulsed lasers if they can be developed and operate reliably, can inflict more damage to many surfaces per joule of energy expended. Here, shock induced high pressures can damage the missile. However, the effectiveness of a pulsed laser depends on the peak intensity on target, pulse shape, laser wavelength, and energy deposited per pulse. For these reasons, the issue of using pulsed lasers to defeat military targets is problematical and depends on the above parameters as well as on the target material properties to determine the level of plasma induced impulse delivered to defeat the target. Whereas the effectiveness of CW lasers primarily relies on the effects of the heat energy deposited on the target. However, unless serious experiments and full scale operational testing takes place, it will be impossible to develop an effective laser weapons system, either CW or pulsed.

Space-Based Interceptors

Space based interceptors (SBI) have the singular advantage of already being on the high ground, unburdened by gravity during an interception maneuver and geographically unconstrained as opposed to land and sea based systems. The APS study points out effective BPI could occur only within ~5 s before burnout, allowing ~ 3 to 4 minutes for interception. This makes BPI from a SBI very difficult to achieve both from the time and range perspectives. Even thenbecause of the vast volumes in space, to have a good chance to achieve numerous BPI hits by interceptor launches from LEO) would require an enormous number of spacecraft that would necessitate the 5-10 fold increase in space launch capability. Maintenance in space of a large number of space-based interceptor platforms could also be problematical if the background orbital debris and meteoroid flux over a long period of time (years) substantially degrades the SBI and their platforms [Remo, 2004].

It may be possible to optimize the advantage of deployed SBIs by using them as post boost-phase interceptors or mid-course interceptors (MCI). That provides verisimilitudes of increasing the amount of time available for interception by almost an order of magnitude. Also, using SBI in the MCI mode will permit shorter fly-out velocities because they could hit a ballistic missile warhead (BMW) at a (roughly) head-on angle and avoid an (ground-based interception) offset tail chase in the BPI. Initial guidance for the SBI can be provided by space based phased array/synthetic aperture radars serving a cluster of interceptors flying in formation. It is also possible to accomplish terminal guidance through a combination of on-board IR sensors and LIDAR or even an on-board homing radar to direct the final kill. Here, heating of the electro-optic guidance components is not an issue because there is minimal atmospheric friction. Since the fly-out and final velocities can be less than 5 km/s, the interceptor booster can be smaller. It will also be easier to determine the trajectory for a BMW in mid-course if it is completely ballistic. Miniaturization is the key technology required for the development of effective SBI systems technology. Smaller KKVs (~ 3 - 5 kg) and boosters will also substantially reduce lift costs, take up less space allowing better debris shielding protection, and will be more difficult to detect and target. Stealth technology can also be used to cloak their activities. For such weapons kill assessments and lethality determination methodologies must also be developed. The design, construction, testing and deployment of such a system within reasonable budget constraints poses a major technological challenge. It will be interesting to see if the aerospace companies can design, build, and successfully test such a system within reasonable budget constraints.

To effectively use a limited amount of SBIs (about 300 to 500 interceptors) to take out BMW in their mid-course trajectories will require careful deployment in space. A disadvantage of MCI is the possibility of a plethora of BMW sub-munitions mixed in with decoys. Other innovative methods that distinguish decoys from genuine warheads are expected to be available within the decade. Laser (lidar), in some cases, may be capable of distinguishing between decoys and genuine warheads. The throw weight of the aggressor is an important factor in the missile defense calculus. It has been stated that for this analysis the missile defense systems studied are for use against an enemy with limited resources or perhaps for the less likely, but much more dangerous case, to deny a first strike capability to a major (symmetric adversary).

An elective pre-emptive strike against a major nuclear/space power would be foolishly counterproductive because such a power is likely to be able to still overwhelm almost any missile defense system from dispersed assets even if many of its other assets are neutralized. It is then implied that SBI may primarily provide a limited missile defense against an asymmetric adversary or (less effectively) to blunt a first-strike action from a better armed adversary. Nuclear conflict among symmetric adversaries is irrational and will lead to global suicide.

Because radar can pinpoint a purely ballistic (mid-course) trajectory it may be easier to intercept in mid-course as opposed the maneuverable boost-phase and the descent stage which is subjected to aerodynamic forces that can be exploited for evasive movements. However, just because MCI targeting may theoretically be more effective than BPI, it does not mean that it will provide adequate defense against a determined effort to use an ICBM to deliver a weapon of mass destruction to the U. S.. But the reality is that a SBI system does not exist and if and when its development is undertaken it is likely that serious design problems will emerge because the physics and engineering tasks of reliably operating an extensive MCI system remotely in space are quite difficult. Here again, the KKV interceptor and its boosters must be built and tested within the appropriate architectural framework before they can be considered an effective ICBM defense system against the current and future threats, and not against the present threats which are likely to escalate unless some serious efforts are made to address the underlying political, social, and economic conflicts that are driving the irrational hostilities.

Other Interpretations

The Missile Defense Agency (MDA) may appear to disagree with some of the APS conclusions and "continue(s) to believe that BPI has great potential for playing a vital role in a layered missile system" [Wall, 2003]. In all fairness to the MDA, their contractors are still involved in the interceptor designs and there is really no missile system developed that can be a "straw man" candidate. It is encouraging that results from recent Navy testing of the SM-3, part of the U.S. Navy's theater-wide protection system against medium and long range ballistic missile attacks, is designed to use a lightweight exo-atmospheric projectile as a kinetic warhead to intercept a warhead in midcourse flight and appears to have achieved some notable successes [Robinson, 2002]. However, the design, development, and testing of the SM-3 missile is for tactical use, not for strategic missile defense. For the SM-3 to take out an ICBM in the BPI stage, the SM-3 would have to be close to the booster and have a higher velocity. Currently, to the best knowledge of the author, no system exists that can reliably carry out a BPI. But this has no bearing on whether the use of MCI can be practical since it would involve a different technology. Also, very high altitude midcourse interception presents its own set of problems that may or may not be tractable by using either ground-based or space-based weapons.

Ultimately, there are two basic issues regarding NMD. First, is it strategically and politically critical to the U.S. national security? Second, is an effective NMD technologically feasible? The former must consider the adversaries response while the latter must realistically evaluate operational capabilities.

Postulated Adversaries in the APS and FAS Studies

While it appears that the APS study raise serious technical questions regarding BPI, it is fair to acknowledge that the metric used to evaluate BPI capabilities is limited to the available knowledge of technology in the public domain, i.e. unclassified and non-proprietary. The APS study also limits itself to launch scenarios against the U.S. from either Iran or the Democratic Peoples Republic of Korea (North Korea) which serve as hostile archetypes if not real threats. (Iraq was originally included but has recently lost its presumed relevance as an ICBM launched nuclear threat). The FAS study is concerned with all types of space-based weapons including electronic, interceptors, satellite communication and control activities, communication links, and other militarily related space operations, both active and passive. In addition, the FAS study on SW does not limit itself to North Korea, Iran, and Iraq as postulated adversarial archetypes. Instead, the FAS addresses threats to and from various types of space weapons and satellites in general, and it does not restrict the dialogue to a few postulated adversaries. Clearly, there are several frightening scenarios that can unfold. Nonetheless, the analysis provided by the APS study is helpful in attempting to provide impartial benchmarks for missile system performance that relate to space based defense systems.

Setting up and launching an ICBM is a complicated operation requiring a complicated operation requiring a large infrastructure and is not a likelyundertaking for terrorists having a WMD since there are so many other inexpensive and simple, better, and more reliable means of delivery that are available. However, there are wild cards in the deck. It is entirely feasible that a terrorist organizations could infiltrate BM facilities and gain control of launch and targeting codes. Missiles could be launched without the knowledge or interference from the central government, especially if the leaders were assassinated and the government was in disarray. While at present these missile may not be able to reach the U.S. coasts, they could nonetheless target U.S. bases, fleets, and allies. After the launch, the terrorists could be evacuated by helicopter or airplane and would not even suffer the retaliation stemming from their actions. This is a realistic scenario for more than one country possessing significant numbers of nuclear weapons and launchers!

The potentially large number and diversity of missiles that could launched by a major nuclear power include the ability to deploy sophisticated countermeasure and decoy capabilities. Such a system can overwhelm a NMD system The geographical and maritime deployment possibilities that could be exercised by such major powers are essentially different problems from those analyzed by the APS study group. In this sense, therefore, the APS study is restricted in scope to those countries thought capable of surreptitiously assembling missile and warhead components to present limited but still quite real threats. It is quite difficult to accept that the leadership of these two (Iran and N. Korea) or any other estranged country would be irresponsible enough to launch ICBMs against the U.S. directly or thorough a proxy when they must realize that the response from the U.S. will be one of overwhelming retaliation. Besides there are issues of range, safety, and yield that present additional uncertainties which must be resolved by actual test detonations and simulated testing of components. Recent or marginal parvenus to the nuclear club are likely to be marginal in thesecategories and thereby creating serious uncertainty regarding the viability of the putative weapons of mass destruction. But as discussed above, fanatics may infiltrate BM facilities without the knowledge of the leadership. This is precisely why nuclear weapons proliferation is so dangerous. The U.S. must remain vigilant against this potential threat.

Conclusion

The technical side to the NMD problem is that one cannot assume appropriate interceptors can be built for effective ballistic missile defense either in BPI, MCI, or terminal defense mode. It is a very difficult task even under the best tactical and strategic circumstances. This is because the time frames within which the detection, ranging, launch decision, and time to intercept are so short the interceptor must travel very fast (~4-10 km/s) depending whether mid-phase or boost phase interception is carried out either from space or the ground. BPI requires faster command, control, and communication (C3) and interception speed which also presents a larger, slower, more luminous, and more vulnerable target than a BMW in space. Achieving targeting, terminal guidance, and effective kill can also present problems for SBI where the target is faster, much smaller, marginally luminous, less vulnerable, and more likely to have deployed its sub-munitions accompanied by decoys. As an example, BPI of a postulated SP ICBM launched from N. Korea would require a ground-based interceptor with a 30 s decision window would require a burnout velocity of ~ 10 km/s. For space-based mid-course interception it is possible to use lower fly-out velocities because there is more time for interception if the SBI collides head-on with the BMW at an angle less than 45 degrees. Here, as in the case of BPI, detection, firing solution, engagement geometry, and kill effectiveness is critical. In all cases, the systems are under a great deal of stress at these high accelerations. Decoys and the release of sub-munitions further compound interception problems. Critical factors include interception time constraints, required fly-out velocities, accelerations and range for anticipated engagement geometry, as well as available interceptor technology, and theater geography (that limits interceptor-based options). Based on these factors, an overall conclusion drawn from the APS report is that using current BPI to defend the U.S. against solid-propellant ICBMs launched from parts of the Democratic Peoples Republic of Korea (North Korea) and Iran is unlikely to be practical whether the interceptor is ground, sea, air, or space based.

BPI has two excellent advantages: first, not having to deal with decoys or other penetration aids and second, defeating the missile at its most visible, slowest, and vulnerable phase. But there are also disadvantages. First, even if the interceptor is in the proper geographical position and along the radar line of sight at the time of the launch the firing window for a successful intercept is only a few minutes. Within this time the correct identification (e.g. that an ICBM, rather than a satellite, is being launched must be made. The system must be ready for interception, and release authority must all work effectively within that short time interval. In a theater war where ballistic missiles are launched over an extended period of time the problems of identification, C3, system readiness, and release authority become much more tractable because launch authority is diffused to lower command ranks (Fowler 2004).

The APS report raises numerous technical issues and questions regarding the feasibility of using ground, air, and space based defenses to protect the U. S. from attack by ICBMs fired by countries that are currently central to the intelligence community's threat assessment. Although the APS study does not include policy issues or tendentious opinions, it certainly implies an immediate urgency for a policy to guide interpretations of the perceived threats from foreign technology and the management of our own technology developed in response to such postulated threats. Technological capabilities alone should not be permitted to control policy. The technical exigency for NMD and hence these (APS and FAS) studies is predicated on the expectation that there are extremist or rogue groups that could gain control by one means or another and would launch NW carrying ICBMs rather than leverage these weapons for political utility.

The APS study focus suggests that isolated and extremist regimes or groups can present a threat far out of proportion to their political and economic influence in the international community. It is important to deal with this threat in a serious and careful manner because a lesson learned from studying the interaction physics of missile warfare is that uncertainty and miscalculation can easily dominate an outcome. Therefore, considering the issues at stake and considering the unpredictability of military conflict in general and missile defense in particular, there exists an important link between national missile defense (NMD) policy and the development and use of missile weapons systems. Because of the asymmetric nature of these uncertain missile threats, a NMD pol-icy must be developed that can provide a way to manage scenarios and technical applications in a non-traditional and non-tendentious manner. Traditional geopolitical concepts that worked well in the past are not relevant in this asymmetric context. Technology will certainly influence but should not be permitted to lead policy either proactively or in response to a perceived technological threat from others. We cannot allow ourselves to be reactive, relying on past thinking when the conflicts were symmetric. Therefore, technological escalation should carefully follow policy guidelinesthat have been clearly thought through. Such a policy should be capable of guiding us in careful deliberations through these ambiguous and yet serious threats that appear to present long term problems and threats to peace.

Acknowledgements

The author wishes to thank G. Canavan, P. Coyle, B. Fowler, J. Impagliazzo, N. Johnson, and I. Roxborough for their critical comments.

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