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The Airborne Laser Anti-Missile Program

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ABSTRACT

This report describes technical issues and congressional options associated with the Air Force's attempt to build and install a multi-megawatt Chemical Oxygen Iodine Laser (COIL) and a complex optical system to direct the laser to the target, in a modified Boeing 747 to destroy short range missiles in their boost phase. As part of its FY2001 budget, the Administration has proposed a significant restructuring of the ABL program which, if approved by Congress, would delay the ABL's first attempt to shot down a missile from FY2003 to FY2005. The ABL program is currently in its Program Definition and Risk Reduction (PDRR) phase, which is intended to produce a full-scale system, with a half-power laser. The current estimated cost of the ABL is $11 billion, including $1.6 billion for the PDRR phase. However, if Congress approves the restructuring of ABL, these costs will increase. The report describes the major systems components, and reviews technical issues associated with the three separate laser systems, the adaptive optics system (AOS) for atmospheric compensation, and the nose mounted turret. The report concludes with several policy options Congress may wish to consider regarding the future of the ABL program. This report will be updated to reflect significant congressional actions or the achievement of ABL programmatic milestones.

The Airborne Laser Anti-Missile Program

Summary

The Air Force is currently attempting to build and install a multi-megawatt airborne laser (ABL) and a complex optical system to direct the laser to the target, in a modified Boeing 747 to destroy theater ballistic missiles in their boost phase. As an operational platform, the 747, along with its multi-megawatt Chemical Oxygen Iodine Laser (COIL) is being designed to destroy missiles in the stratosphere above 40,000 feet (12 kilometers), within one to two minutes after launch, at ranges of up to several hundred kilometers (km).

The 1991 "Gulf War" raised concerns about the destructive capacity that small nations can possess in the form of short range missiles capable of carrying highly destructive warheads. This capability motivated the U. S. military to seek an effective means of defense against missiles of short to intermediate range, the so-called theater ballistic missiles (TBM).

The ABL program is currently in its Program Definition and Risk Reduction (PDRR) phase. The PDRR is intended to produce a full-scale system, with a half-power laser. However, the FY2001budget proposal includes a significant restructuring of the ABL program which, if approved by Congress, would delay the ABL's first attempt to shot down a missile from FY2003 to FY2005. Under the current budget proposal, funding for the ABL program would be cut $903 million between FY2001 and FY2005. The current estimated cost of the ABL is $11 billion, including $1.6 billion for the PDRR. If the proposed restructuring is approved by Congress, these costs would increase.

The Air Force contends that the ABL utilizes "mature" technology capable of destroying enemy TBM at ranges up to hundreds of km. Others, including the Air Force Scientific Advisory Board, have characterized ABL key technologies as "experimental." The congressionally mandated Independent Assessment Team (IAT) identified a number of technical challenges facing the ABL including laser power generation, laser beam pointing and tracking capabilities, prediction and compensation of atmospheric distortion, and the use of enemy counter measures to defeat the ABL. The IAT also indicated that the Air Force revised PDRR testing plan to address these challenges should "reduce the risks and narrow uncertainties of the ABL program."

Congressional concerns about the ABL have been expressed since its inception. In FY1999 these concerns centered around two main issues. The first is the belief that the Air Force had not adequately demonstrated the feasibility of the necessary technology to begin "such significant investments" needed to complete PDRR. And second, that testing necessary to make important decisions about the technological viability of the ABL program will not occur until FY2003, just prior to ABL entering EMD, one year *after* the Air Force is scheduled to order a second unmodified 747. The Air Force conducted a number of additional tests in 1999 to address a number of these congressional concerns. The results of these tests are discussed in the report.

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Introduction

Air Force Restructures the ABL Program

As part of its FY2001 budget, the Administration has proposed a significant restructuring of the ABL program which, if approved by Congress, would delay the ABL's first attempt to shot down a missile from FY2003 to FY2005. Under the current budget proposal, funding for the ABL program would be cut $903 million between FY2001 and FY2005. The Air Force requested $148.6 million for the ABL in FY2001, $92 million below the planned level of $241 million. Congress appropriated $309 million for ABL in FY2000. The ABL is designed to shot down theater ballistic missiles during their boost phase.

The $11.3 billion program is currently in its PDRR phase ($1.6 billion) and was scheduled to move into an EMD program in March of 2003. If Congress were to approve this proposal (which is likely to receive considerable opposition in both the House and Senate), it is likely that the program would not enter EMD until after 2005. Further, according to the Air Force, programmatic delays will result in significant cost increases for the entire ABL program.

The Air Force has placed the ABL on its unfuded priority list (UPL) that is submitted to Congress. This list consists of Service programs, in order of priority, that the they would fund if Congress appropriated more for defense spending than originally requested by the Administration. The FY01-FY05 ABL UPL request restores $873 million of the proposed $903 million reduction. The Air Force $241 million plan request for ABL.

The PDRR plane has recently begun its 18 month modification to accommodate the six module COIL and the 14,000 pound nose turret and related structure that will be used in both ground and flight test of the modified ABL system. If the restructuring program is implemented all of the major programmatic milestones dates, contained in this report, will be delayed by a minimum of two years.
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The Air Force is currently attempting to build and install a high powered airborne laser (ABL) in a modified Boeing 747 to destroy theater ballistic missiles in their boost phase. As an operational system, the 747, with its multi-megawatt chemical laser is designed to destroy missiles in the stratosphere above 40,000 feet (12 kilometers) within one to two minutes after launch, at ranges of several hundred kilometers. If the Air Force's Program Definition and Risk Reduction (PDRR)[1] activities meet their technological expectations, a modified ABL is scheduled to achieve its first shoot down of a missile in FY2003.

The 1991 "Gulf War"raised concerns about the destructive capacity of short range missiles (often referred to as Scud missiles) capable of carrying highly destructive warheads. The growing possibility that developing countries may be able to deliver chemical, biological, or nuclear weapons has motivated the United States to seek an effective means of defense against missiles of short to intermediate range, the so-called "theater" missiles. Each of the three Services is developing theater missile defense systems. The Army and Navy are developing five Theater Air and Missile Defense (TAMD) systems (to counter lower tier, or short range missiles within the Earth's atmosphere and upper tier long range missiles above the Earth's atmosphere or in the upper atmosphere) under the Ballistic Missile Defense Organization (BMDO).[2] While the ABL program is managed and funded by the Air Force, it is coordinated with BMDO. From an operational perspective, it is designed to be integrated with the other Services' TAMD systems.

The ABL has several characteristics which are unique with respect to the other TAMD systems. First, the ABL is designed to destroy its missile in the *boost phase,* within approximately the first two minutes of flight. For reasons that will be discussed in the report, unlike other TAMD weapons, the ABL laser is unable to destroy a missile once the boost phase is complete. Second, the ABL will be capable of detecting and locating the missile from the moment it is launched (under ideal conditions, e.g. minimal cloud cover) and throughout the boost phase. While the ABL is being designed to coordinate its effort with the other Services' theater defense activities, the ABL, would be capable of operating independently of the other Services' TAMD systems.

Third, the ABL also serves as a surveillance vehicle. Its precision tracking and projection of target destinations of missiles and aircraft can be passed on to the Army and/or Navy theater operations command for use with other missile defense assets. Fourth, the ABL could be designed to attack other airborne threats such as aircraft and anti-aircraft missiles, and ground base threats using optical sensors for detection and guidance. Finally, given the planned mobility of the ABL, the Air Force contends it can be deployed to an area or region of potential conflict within 24 hours and quickly repositioned as the conflict shifts in direction or extent. Thus the Air Force

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[1]According to DOD the primary purpose of a PDRR is to demonstrate critical manufacturing practices by gathering engineering data for the engineering, manufacturing and development (EMD) phase and building a prototype in order to enhance program confidence by shooting down several missiles at appropriate ranges. This involves examining alternative program acquisition strategies in order to develop program costs, including total life cycle costs. A successful PDRR should ensure that technology, manufacturing, and support risks "are well in hand," before moving into EMD.

[2]For further details see: Congressional Research Service, *Theater Air and Missile Defense: Issues for Congress,* by Robert Shuey and Lisa Meyer, CRS Issue Brief 98028, updated regularly.

views the ABL as a highly flexible weapon that can also help attain its core mission of securing and maintaining air superiority during conflict.

The actual success of a "directed energy"[3] weapon depends on the killing range of the weapon, in this case a high powered chemical laser. Other critical parameters of the ABL are the accuracy with which the laser can be pointed, the length of time the laser stays on target, and the energy the laser can place on the missile. While the Air Force has a long history in experimenting with laser weapons, the ABL would be the first fully integrated computer controlled system for target detection, tracking, and firing a multi-megawatt laser as an anti-missile weapon.

Three advances in technology since the early 1980s have increased the possibility that a successful ABL can be built: 1) the increased power and speed of microprocessors needed for the evaluation of complex algorithms (mathematical formulas) for systems operations and control; 2) steady improvements in the development of adaptive optics to insure the arrival of the sufficient laser power on the target; and 3) the steady improvements in the development of an efficient, light weight chemical laser. Without all three of these developments this program would not now be feasible. However, there remain some complex technical challenges that must be overcome in order for the ABL to be built and successfully tested.

Responding to congressional concerns and the recommendations of the congressionally established Independent Assessment Team (IAT), the Air Force added risk reduction activities and significantly expanded the PDRR test program, and revised its estimates life-cycle cost of the ABL program. This estimate includes $1.6 billion (a $300 million increase) for the current Program Definition and Risk Reduction (PDRR), $1.1 billion for the engineering and manufacturing development (EMD) phase, $3.6 billion for the production phase, and $4.4 billion for 20 years of operations and support. If the Air Force's PDRR activities meet its technological expectations, a PDRR prototype ABL is scheduled to achieve its first shoot down of a test missile in late FY2003. If this shoot down is successful, the program will move to a two year EMD program in FY2004, assuming that the long lead items have been ordered.[4]

The report begins with a brief history of laser research in the Air Force. This is followed by a description of the major subsystems that make up the ABL. Next the report provides an overview of the technical and programmatic challenges confronting the ABL program. The paper concludes with a discussion of congressional issues and options regarding ABL.

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[3]A directed energy weapon kills its target by delivering energy to it at or near the speed of light. Includes lasers and particle beam weapons.

[4]Spending estimates from official Air Force documents.

A Brief History of Weapons at the Speed of Light[5]

The Department of Defense (DOD) has been exploring the possibility of using lasers as both offensive and defensive weapons since the early 1960s. By the mid-1960s all three Services had established task forces to study the use of lasers as potential future weapons. In the early 1970s, the Air Force contracted with General Dynamics Corporation to build an Airborne Laser Laboratory (ALL) and with Hughes Aircraft to design and build a Airborne Pointer Tracker laser. In 1983, after nearly ten years of research, the Air Force announced that the ALL had managed to "destroy or defeat" five AIM-9 Sidewinder air-to-air missiles and a BQM-34 drone.[6]

These tests did demonstrate that a high-powered laser (but with much less power than the ABL laser) mounted in an airplane could destroy a missile. Further, the ALL use a human to initiate the separate computer controlled pointing and tracking system, shot at a range of only 10 km, and, did not utilize atmospheric compensation to correct the distortion of the laser beam. The table below presents some key dates in the Air Force's quest to develop an airborne laser.

What It Takes To Build an ABL

The ABL is a complex system of state-of-the-art technologies. It utilizes three powerful lasers, a variety of infrared sensors, and delicate precision optics. Powerful computers and complex software control its operation. The ABL is composed of several major subsystems which address the functional requirements of detection, tracking, aiming and adjusting the lethal laser beam, and destruction of the missile. A final challenge involves integrating the subsystems into a working weapon on board a specially modified aircraft.

The term ABL designates an aircraft carrying a multi-megawatt laser[7] and a complex optical system to direct and "refocus" the laser beam, as it travels through the atmosphere, towards the target. The ABL system is designed to cruise in a safe

Table 1 Brief History of Air Borne Laser

Year	Activity
1970's & early 1980's	Airborne Laser Laboratory (*ALL*) experiments with a CO_2 Laser testing various directed energy possibilities.
1983	ALL demonstrates the destruction of a missile with a laser, at short range.
1980's	Laser radar tracking widely used for short, horizontal ranges.

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[5]Table developed by CRS, information provided by the Air Force.

[6]Air-to-air missiles are aircraft mounted missiles designed to shoot down enemy airplanes.

[7]The potential power level of the COIL laser is classified information.

1980's	Adaptive optic systems actively researched and demonstrated in the laboratory, leading to applications in observational astronomy.
1980 - 1985	MIRACL/SLBD a ground based Deterium Floride laser destroys a variety of missiles at short ranges.
1987	COIL laser module produces 25 kW output at 1.315 micrometers.
1993 - 1995	Tests, measurements, and analysis to develop techniques for adaptive optics to compensate for air turbulence (i.e. ABLEX 1993, ABLE-ACE 1995, et al).
1996	COIL demonstrates high power capability in one module.
1996	Active tracking of boosting missiles demonstrated at short ranges (Black Brant Active Track).
1997	MIT/LL[8] demonstrate closed loop tracking and AOS beam compensation on static target (Firepond Project) at 5.4 km. Demonstration design scaled to 200 km at a bandwidth of 100 Hz.
1997	Boeing successfully tests modified 747 scaled configurations for the nose turret and exhaust manifold in a wind tunnel.
1998, May	Lockheed Martin (L-M) tracking, laboratory tests demonstrate tracking to 100 nano-radian (0.02 arc seconds of angle) accuracy.
1998, June	Authority to Proceed-1 (ATP-1), OSD and AF give authority to proceed with some conditions.
1998, July	High power laser tests of exterior coatings to prevent heat damage of representative deformable mirror are successful.
1998, September	COIL tested with new, light weight components, achieving 110% of required power at a weight of 1410 kg.

[8] Massachusetts Institute of Technology, Lincoln Laboratory

zone of a combat theater, behind friendly lines, where it can detect, track, and fire the high powered laser to destroy theater ballistic missiles (TBM) launched from the enemy territory. For technical reasons, missile destruction must take place during the boost phase of the missile and above the clouds, at elevations in excess of 40,000 feet. Below this altitude atmospheric visibility can be obscured by clouds, and the atmosphere has a great deal of turbulence. These two conditions can hinder the detection and precision tracking of the missile early in its boost phase, thereby limiting the lethality of the chemical oxygen iodine laser (COIL).[9]

One of the advantages of early destruction of the missile is that the warhead with its payload is likely to fall onto enemy soil. Older TBMs (e.g. scuds) have a range of about 200 km- 300 km, while new TBMs have ranges that can exceed 1,000 km, depending on the payload, and the material the missile is made from (i.e. aluminum or steel).

As previously indicated, the ABL is designed to be completely autonomous in that it can detect, locate and destroy a missile without assistance. Figure 1 shows a layout of the ABL in the aircraft. The multi-megawatt COIL laser is positioned in the rear portion of the fuselage. The lethal beam travels in a helium filled tube to the beam control unit in the nose of the aircraft. The beam control unit compensates (focuses) the beam and projects the beam through a window in the nose of the aircraft, directing it at a target hundreds of kilometers distant. In addition, there are infrared sensors and trackers for detecting and locating additional missiles while the ABL is engaging an identified target.

The ABL will have to carry the chemical laser fuel on board the aircraft (see figure 1). The Air Force estimates that the current laser fuel carrying capacity will allow the high powered laser an estimated 20 to 40 shots at a number missiles, before requiring the plane to return to base for refueling the weapon. However, capacity could be less than 20 to 40 shots depending on the duration of each shot, which is expected to last a number of seconds depending on range and atmospheric disturbances.

The following sections describe the major subsystems that comprise the ABL.[10]

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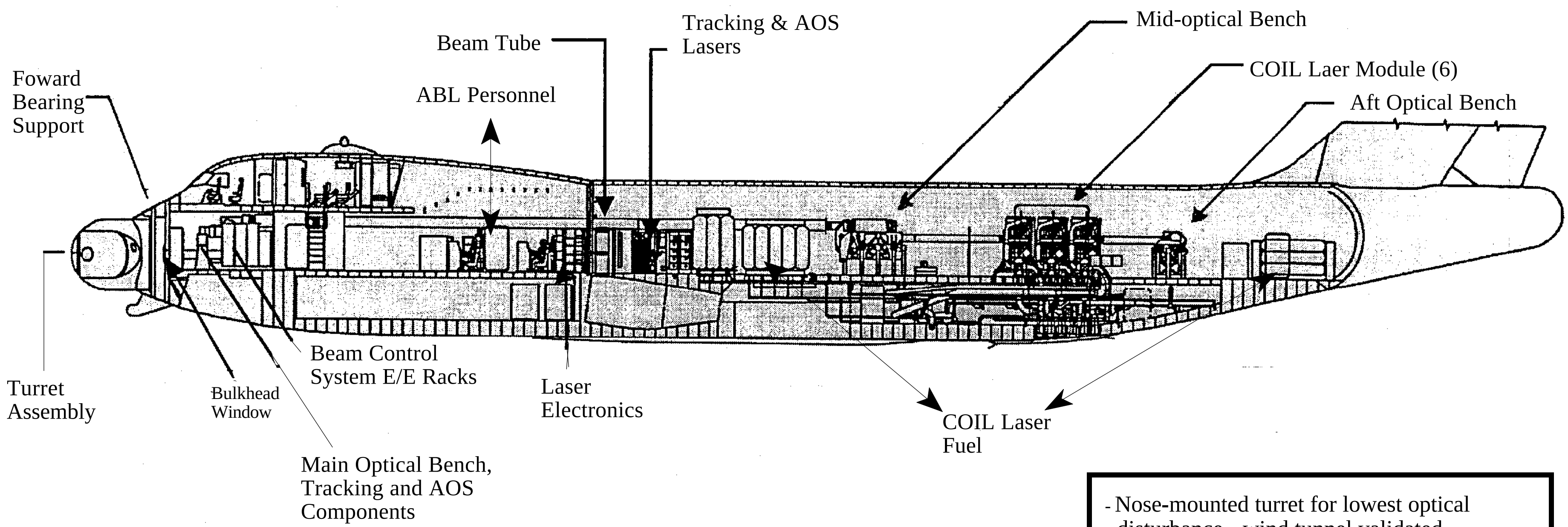
[9]Chemical lasers produce power as a high-energy beam of concentrated light derived from chemical reactions, in this case between excited oxygen and iodine atoms.

[10]Most of the following descriptions are taken from official Air Force documents.

Beam Control/Fire Control Key Design Highlights



- Nose-mounted turret for lowest optical disturbance - wind tunnel validated
- Adaptive optics for atmospheric compensation - brassboard validated
- Common Path/Common Mode sensing and controls - experimentally validated
- Vibration isolation data - flight validated
- ATP/Fire Control algorithms optimized - anchored models, ground test validated

Figure 1: ABL System Configuration in a 747F-400 Boeing Aircraft
Source: Air Force Briefing at Lockheed-Martin, October 28, 1998

Detecting the Missile

First, the missile must be detected and located. This may take place with either on-board sensors designed to detect the heat radiated by the exhaust plume from the rocket, or, alternatively, a satellite or other surveillance vehicles that can detect and locate the firing of a rocket in the theater of action or war zone.

The ABL aircraft will carry several Infrared Search and Track Sensors (*IRSTs*), which will allow the tracking of more than one missile launch. IRSTs is used to detect signal characteristics of hot missile exhaust. Once the launched missile has been located, these IRSTs establish an initial coarse track of the missile trajectory. As information on the trajectory accumulates it will be conveyed to the main ABL computers. The detection and coarse tracking equipment employs mature technologies which have been used on military aircraft and satellites for a number of years.

The Chemical Oxygen Iodine Laser (COIL)

The COIL is a dual-line, multi-module laser operated as a single, unstable resonator (continuous beam), with the cavity mirrors installed midship and a pair of turning prisms at the rear to complete the beam path (see Figure 1). Located near the exit mirror, a "deformable" mirror cleans up the beam profile as it leaves the laser. Chemicals for fueling the laser, along with the plumbing are stored in the central and rear portions of the fuselage.

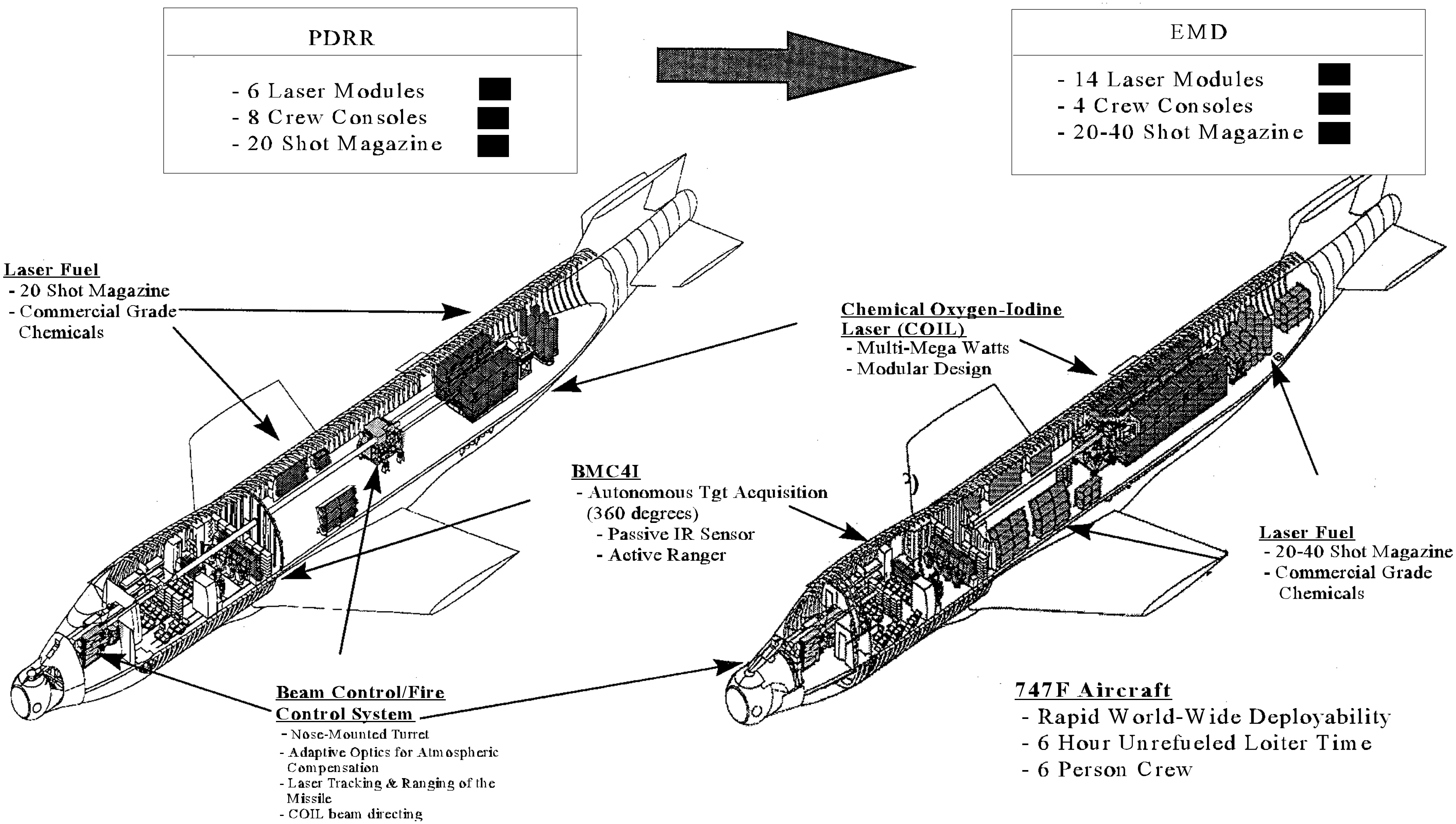
According to the Air Force, the COIL laser provides sufficient power to destroy missiles up to several hundred kilometers under various atmospheric conditions. The initial PDRR demonstration aircraft will use six lasers (2 rows, 3 lasers in each row) to producing more than a megawatt (*MW*) of power. The actual operational system will have 14 lasers (2 rows 7 lasers in each row) which will produce several megawatts of power (see Figure 2). This is a significantly higher level of power than has been produced with a continuous or semi-continuous ground based chemical laser. Lasers are inherently inefficient devices, in that they convert only a small fraction of the input energy into laser light energy; most of the energy is dissipated as heat. The limited availability of electrical power on an aircraft precludes using electrically powered lasers of the megawatt size. The chemical laser uses the energy resulting from the chemical reaction of several chemicals to power a laser without massive use of electrical power. The COIL chemical energy is supplied by the reaction of hydrogen peroxide and chlorine. To obtain its destructive power this laser must sustain high power output for a number of seconds and produce a high quality beam. Designing and constructing the high power laser for installation aboard an aircraft are some of the more difficult engineering challenges for this project.

Precision Tracking

This section and the following two sections on adaptive optics and the nose mounted turret describe the Beam Control/Fire Control system (*BC/FC*). Located forward in the airplane is the Beam Control/Fire Control system comprising a

ABL System Design

Figure 2: ABL System Design from PDRR to EMD



Source: Figure provided by the Air Force.

complex optical system which tracks the missile, the atmospheric compensation subsystem, and the 1.5 meter laser beam steering mirror, mounted in the rotating nose turret with the 1.74 meter window (see Figure 2).

The ABL system uses the coarse tracking data from the IRSTs sensors to initiate the precision tracking system to direct the lethal laser. The tracking unit operates as a separate laser radar system. A powerful, pulsed laser is directed at the target. Some of the light is reflected off the target missile and returns to the tracking unit on board the airplane. A detector collects this light and a computer processes the sensor signals to form an image of the missile. The tracking laser locks onto this image to track the trajectory of the missile. This is a time critical operation. The ABL must lock onto the missile within several seconds depending on the range of the missile.

The ABL system requires this tracker to locate, within tens of centimeters, the front of the missile at distances of several hundred kilometers. The need to concentrate the energy from the lethal laser onto the body of the missile drives this high precision requirement. Moreover, when the tracking system first locks onto the missile it may only be traveling at mach 1.[11] But, by the time the system is ready to fire the COIL laser the missile will be traveling at mach 2 or faster and continually accelerating until burn-out or destruction.

The tracking subsystem consists of a number of mirrors including the output mirror, 1.5 meters in diameter, that directs the lasers at the target. The mirrors are mounted on a special bench that keeps them in precision alignment. The COIL's beam is directed through some of the same optics to the missile. The tracking laser has a slightly different wavelength than that of the COIL and thus the tracking laser operates independently of the COIL.

Adaptive Optics System (AOS)

As the COIL beam propagates through the atmosphere to the target missile it encounters turbulence, water droplets, ice crystals, and temperature variations which can distort the beam and cause it to lose focus on the missile (see Figure 1). A very common phenomenon, such distortion can be seen by viewing a distant object through air rising off hot pavement. If the COIL beam encounters atmospheric turbulence it will, if uncorrected, lose focus and become ineffective in destroying the missile. The purpose of the AOS is to compensate for the beam distortion to ensure the beam has sufficient coherent energy to destroy the missile.

Here is how it works. A separate "beacon" laser generates a string of rapid light pulses which scatter off the missile. In the same manner as the tracking laser, the AOS collects and analyzes the scattered pulses to measure the distortion produced by the atmosphere. The AOS utilizes this measurement to reshape a special computer controlled deformable mirror, which distorts the outgoing COIL beam to compensate for the distortion resulting from atmospheric turbulence. Experience with astronomical applications and other laboratory studies have shown that this beam compensation will focus more energy on the missile target, maintaining its lethality

[11] Mach 1 is equal to the speed of sound or approximately 1150 feet per second, at sea level.

instead of losing it because of dispersion in the atmosphere. The ratio of the focused power in the actual beam to that of a perfectly focused beam is known as the **strehl ratio** (*SR*).

However, it is important to note that if the initial beam produced by the COIL is insufficient in terms of power and/or coherence, the AOS will not be capable of "correcting" what the COIL was unable to produce initially.

The Nose Mounted Turret

Another crucial component of the ABL is the approximately 12,000 pound turret in the nose of the modified 747 aircraft. The turret carries both the 1.74 meter window and the 1.5 meter pointing mirror. The latter is mounted on a gimbal that rotates the mirror to point the laser beams at the target. The turret field of regard covers the forward hemisphere of the aircraft, and the aft portion almost to the wings.The nose window is a critical optical component for ABL All three laser beams, the passive image of the missile plume for the plume tracker, and the return signals for the fine tracker and the atmospheric compensation subsystem, pass through this window.

Aside from purely structural engineering, the window has several system level requirements: 1) the shape, location, and installation must minimize the exterior boundary layer turbulence around the window so as to minimize optical distortion in the COIL beam; 2) beam distortion (birefringence) due to mechanical and thermal strain in the window must be minimized; and 3) there must be low absorption and scattering of the laser light as it passes through the window and is reflected off the target back to the ABL optical system.

Systems Integration

Boeing is the prime contractor and is responsible for overall management of the ABL program, including the significant challenge of systems integration. Boeing has developed plans to modify a 747-400 aircraft for the ABL. Besides accommodating the COIL and the BC/FC, two major components of Boeing's aircraft modifications are: 1) the rotating nose window which also carries the 1.5 meter pointing mirror, and 2) the laser gas exhaust system. Since the interior of the aircraft, will be noisy, particularly when the lasers are operating, Boeing is investigating the need for enhanced communication equipment among the flight crew and ABL operators.

The ABL computer controlled command and control center must coordinate all the activities of the three lasers on board. This includes acquiring the initial information on the location of the missile launch, initiating the pointing laser, the precision tracking laser and the subsequent follow on activities of the tracking laser beam adaptive optics system (AOS), concluding with the firing the COIL. All of this must take place in 30 seconds or less as the missile accelerates to high velocity in its boost phase.

To aid in the systems integration tasks, Boeing is using the CATIA, a sophisticated computer design tool used in building its commercial aircraft. This computer design tool allows Boeing, or any other ABL contractor, to make a "blueprint" change in one ABL subsystem that will automatically be reflected in other subsystem drawings, if necessary. The software engineering makes use of the existing Boeing Open System Architecture and all builds are tested in a virtual ABL facility at Boeing.

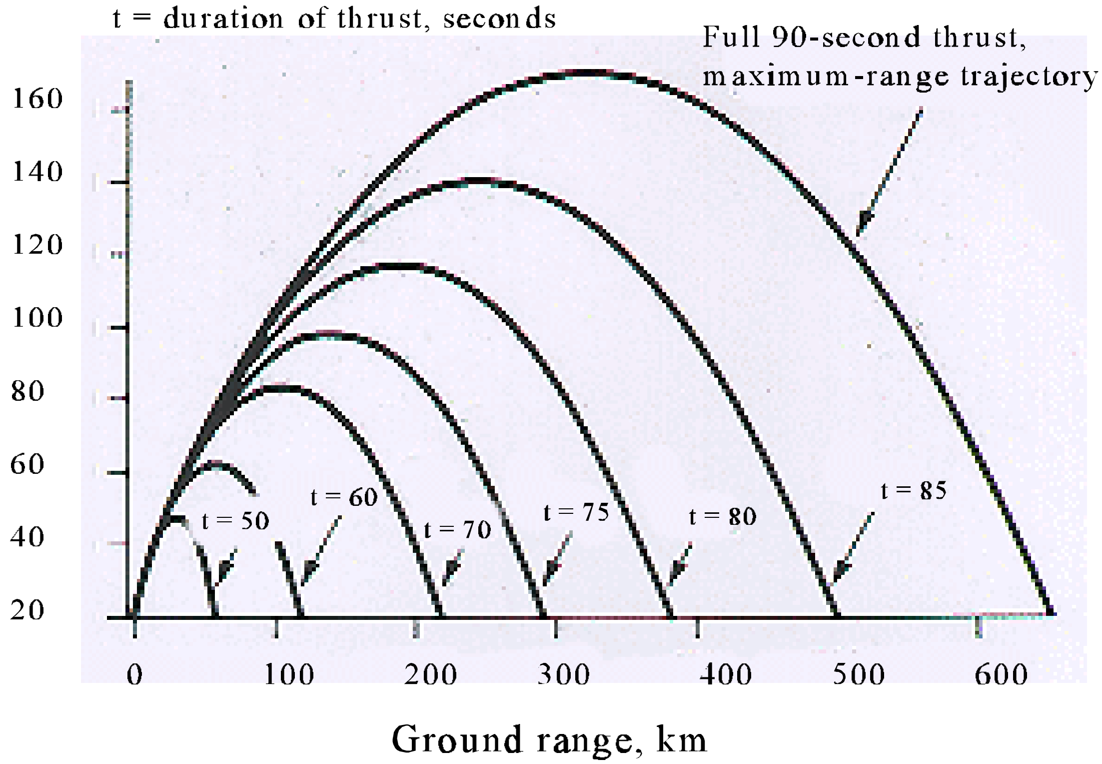
General Systems Operations

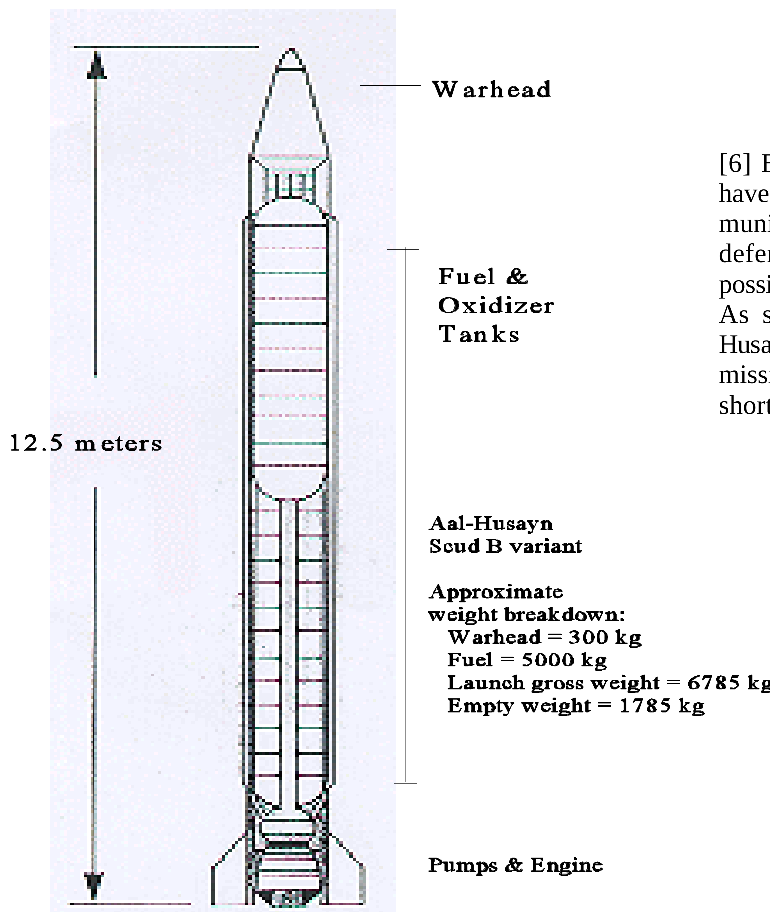
Cruising in a safe fly zone, probably behind the battle lines, the ABL is capable of operating as an autonomous platform designed to detect, target, and destroy theater missiles aimed at local military assets. ABL relies on either its on-board detecting equipment, or standard airborne or satellite detection equipment now in service to detect a missile launch. Once located, the ABL initiates its laser radar tracking subsystem to lock on to the moving missile and track its position to high accuracy. The AOS, utilizing a second laser, sends and receives signals from the target to measure the atmospheric turbulence in the path of the laser beams. The AOS converts these measurements into corrections that help "re- focus" the power of the COIL beam on the target. In a matter of seconds, the multi-megawatt, COIL is focused on the missile for several seconds, depending on the distance to the target, to destroy the missile.

Below an altitude of 12.5 kilometers (about 41,000 feet) atmospheric visibility can be obscured by clouds and atmospheric turbulence. These two conditions would greatly hinder the detection and precision tracking of the missile early in its boost phase, and they can limit the lethality of the system. Consequently, the general consensus among the engineers and the Air Force is that the best time to attack the missile is as it enters the stratosphere, above the clouds where there is less atmospheric turbulence, and before the boost phase terminates. Notably, the latter part of the boost phase also coincides with large acceleration and stress on the missile.

The ABL is designed to destroy the missile during the boost phase because: 1) the rocket is highly vulnerable to disruption while it is under power; 2) it is relatively easy to detect and track its exhaust plume; and 3) the laser beam destroys by destructive heating of the stainless steel missile body.

Figure 3 displays the characteristic features of a typical short range missile. The main body of the missile, between the conical warhead and the engine at the base of the missile, is mostly fuel tanks. The warhead is about two meters in length, and the engine, comprising turbo pumps and a combustion nozzle , occupies about two meters at the base of the missile. At take off, 75-80% of the weight of the rocket is fuel contained in a thin metal casing. The six to eight meters of the main body carries the fuel, oxidizer, and a guidance system; it is considered the most vulnerable region for the laser. Focusing the tracking laser on the warhead provides the information needed to guide and focus the lethal laser





[6] Because an enemy missile may have chemical or biological submunitions, a goal of boost-phase defense is to have it fall as close as possible to the attacker's territory. As shown here with the Iraqi al-Husayn as an example, the earlier a missile's thrust is terminated, the shorter its range.

Figure 3: Typical short or medium range missile
Source: The Airborne Laser, G. Forden, IEEE Spectrum, September, 1997

on the missile body in an effort to penetrate one of the fuel tanks. As the laser heats the missile casing to a high temperature, the combination of internal fuel pressure and axial stress on the missile from the thrust of the engine may cause one or more of the following:

- The internal fuel pressure may rupture the tank and the fuel will leak out. At a minimum, the rocket would prematurely terminate its boost phase and fall short of its target destination.
- The launching forces on the rocket under acceleration may collapse the body of the rocket causing it to fragment and the warhead would veer off and possibly fall in the vicinity of the launch site.
- Less likely, leaking fuel may detonate and destroy the rocket and its warhead.

It is important to note that destroying the missile does not automatically destroy the warhead; its ultimate fate is largely speculative at this time. The reason for this is in the dynamics of launching a ballistic missile, which is similar to firing a rifle. The launch begins with an explosive burst of energy for a minute or two, the boost phase, followed by four or five minutes of coasting to the target. The rocket launches vertically. About one-third of the way through the boost phase it has attained the velocity of mach 1 and an altitude of more or less five kilometers. At this point the rocket thruster shifts to aim the rocket at the target. The boost phase continues for another 30 or 40 seconds at which point the missile is traveling many times the speed of sound and is climbing through an altitude of 30 or 40 kilometers (18-24 miles). The missile or warhead coasts on the remainder of its trajectory to the target. Some long range ballistic missiles may have the capability of small mid-course corrections and some detach the warhead from the rocket at the end of the boost.

Table 2: Approximate Values for SCUD Missiles Currently Fielded[12]

Parameter	**SCUD-A**	**SCUD-B**	**SCUD-C/ al-Husayn**	**NODONG**
Length (m)	11.25	11.25	11.25	15.5
Diameter (m)	0.88	0.88	0.88	1.3
Range (km) Payload (kg)	300 985	300 985	500 700	1000 1000
Fuel Fraction	0.74	0.74	0.77	0.80
Boost Time (sec)	70	70	87.5	70*
No. of Engines	1	1	1	4

* Others, including Boeing, estimate a considerably longer boost phase.

[12] Table developed from data in, *Analysis of the North Korean NoDong Missile*, Wright & Kadyshev, Science & Global Security, Vol 2, N. 4, 1994; various articles in IEEE Spectrum, September 1997; and private communication with Geoffrey Forden, at the Congressional Budget Office.

All of the above launch estimates scale in time with the range of the missile as indicated in Figure 3. A scud type missile going for a target at 100 kilometers arrives in two minutes with a boost phase of 30 or 40 seconds. However, at 600 kilometers the missile arrives at the target in six or seven minutes, with a boost phase of 70 to 90 seconds. Table 2 lists the principal attributes of the missiles currently in the field. Also, it is possible to reduce the payload in order to obtain a marginal extension of the range.

The Air Force also sees the ABL performing other defensive and offensive TMD missions in the theater operations. Besides destroying the missiles, the Air Force contends ABL could track them with high precision providing essential information to the Army and Navy terminal defense operations and warn the target areas of the impending attack. The Air Force is currently analyzing the potential of ABL to defeat airborne threats (i.e. aircraft and missiles) for self protection and the protection of other high value airborne assets in the immediate combat area.

There are many thousands of older SCUD missiles deployed around the world with a range of 300 km or less, which, according to the Air Force, the ABL is well designed to attack and kill. While some critics consider that long range missiles will be inaccessible to the ABL, the Air Force contends that the ABL could provide an additional capability against these missiles and essential information on their trajectories.

ABL Technical Challenges

As previously noted, the basic requirement for the ABL is to destroy a missile from a range of several hundred kilometers, within a couple of minutes after launch. At shorter operational ranges (distances less than half of the expected ABL operational range)[13] it is likely that the Air Force can build an airborne laser system that would knock down a missile shortly after it was launched, under reasonably ideal conditions. But can a system be built that will deliver energy to a missile at ranges of several hundred km sufficient to destroy the missile? This is the essential question that defines the system's efficacy. Why is the range parameter chosen? Although the Air Force emphasizes the existence of thousands of short range SCUD missiles scattered around the world, Table 2 shows an evolving trend towards longer range and high thrust missiles for theater operations. This implies that either the ABL must penetrate into enemy territory or destroy the missile from a long range. In addition to range, the lethality of the ABL during combat depends on other parameters such as the variety of atmospheric conditions in which it will operate, the variety of counter measures that could be employed, and the system’s ability to respond to random events, such as the launching of several missiles simultaneously.

The following sections examine performance estimates and technical challenges for the major subsystems, as well as overall systems integration. The analysis is based on basic scientific principles and information on relevant technologies found in the open literature. The objective of the analysis is to determine the extent to which a

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[13]Because of classification concerns, specific operational distances of the COIL can not be revealed.

system is capable of destroying a missile in its boost phase at ranges of up to several hundred kilometers.

BF/CF: Tracker and Adoptive Optics System (AOS)

As part of the beam control, fire control (BC/FC) system, the tracker and the adaptive optics system (AOS) uses relatively new technology that has been widely implemented in modern astronomy but has never been employed with high power lasers such as the COIL. The Air Force has performed a number of experiments on AOS components to determine how atmospheric turbulence affects the propagation of a laser beam. One such experiment (The Firepond Experiment) involved a short range (5.4 km), closed loop tracking test on a static target at the MIT Lincoln Laboratory which demonstrated that the strehl ratio (SR--level of beam coherence) for an uncompensated beam can be increased by a factor of four with an AOS. This demonstration simulated the ABL conditions for a range of 218 km in the stratosphere. It is also important to note that the target was not moving.

One of the key components of the AOS is the deformable mirrors which modulate the laser beam to compensate for atmospheric distortions. The final AOS optics bench will utilize three 30 cm deformable mirrors with 261 computer controlled actuators. A 10 cm version of this mirror, with the appropriate number of actuators and special optical coating to prevent the mirror from over heating, has been built and tested at laser power levels exceeding those expected in the fully operational system ABL.

A working model of the tracking system has been tested at both the Lincoln Laboratory and in the Lockheed Martin (LM) laboratory. According to Lockheed Martin, it utilized simulated atmospheric turbulence and achieved the required tracking accuracy specified by the Air Force's ABL functional requirements. Both the AOS and the tracking system are using an electron beam charged couple detector (*EBCCD*), a relatively new technology, for a high efficiency, low noise imaging detector. There will be two of these EBCCD sensor units on the ABL, one for the fine tracker and one for the wavefront sensor.

Despite the success of the Lincoln Laboratory test, the Independent Assessment Team (IAT)[14] indicated that atmospheric compensation has not yet been demonstrated at operational flight altitudes. The IAT report noted that while the initial detection of the missile launch plume should not be difficult, the steps leading to the destruction of the missile will be very challenging. Once the missile has been detected, the ABL pointing and tracking lasers must "acquire and measure the distance to the apparently small, dim target with a ranging laser; and then while maintaining very tight jitter control, precisely place and hold on the missile two medium-power laser illuminator

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[14] As Part of the FY1999 Defense Authorization Act, Congress directed the Secretary of Defense to charter an Independent Assessment Team to review the technical and operational aspects of the ABL program.

beams, or, tracking beams (that will generate returns that might be noisy and weak) and a turbulence compensated COIL laser beam."[15]

While the Air Force ABL officials are confident that the pointing and tracking lasers will meet operational requirements, others in the Air Force, as well as the other two Services, are concerned that the tracking laser may not be capable of tracking theater ballistic missiles (TBM) at the longer operationally required distances. The IAT has recommended that the AF conduct more rigorous dynamic testing (using moving surrogate targets, including airplanes and other appropriate targets) in order to gather more data on the operational effectiveness of the pointing and tracking lasers.[16]

COIL Power

Once the target has been acquired, the COIL beams high power out the turret window and onto the target. The energy deposited on the target causes the missile casing to heat, and when the local temperature reaches the yield (destructive) temperature for the metal, the internal stresses on the casing will cause it to fail and the missile will break up. The success of the COIL is critical to the future of the ABL as currently designed. An airborne laser of this magnitude has never been built. The four major design drivers are: weight, size, power, and beam quality. In September of 1998, a single laser module with the appropriate size required for the aircraft, and flight-weighted to 3104 pounds (1410 Kg), was tested to better than 110% of design power. From this test, the engineers have initiated some design improvements to be implemented for the next version of the flight-weighted COIL.

However, a recent General Accounting Office (GAO) report questioned the validity of the COIL power and quality measurements for two reasons. First, the AF tested a flight weighted COIL that contained some key components which were not representative of the COIL that will be deployed in the operational ABL. Second, while the AF indicated that beam quality was satisfactory, the AF did not "fire the laser" and simultaneously measure beam power and quality. Although the AF measured output power directly, beam quality was estimated using software models.[17] While it is not always possible or practical to "hot" measure the beam quality of a high energy laser, using software models to estimate beam quality for a flight weighted laser that has never been fired raises obvious concerns. AF representatives have noted that their approach for measuring power and quality complies with scientifically accepted methods for estimating power and beam quality during the testing and development of a high energy lasers. The Chairman of the IAT, Thomas Marsh indicated that he had confidence in the Air Force's test results of the COIL.

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[15] Assessment of Technical and Operational Aspects of the Airborne Laser Program. March 9,1999. Secretary of Defense comments on IAT report, P. 7.

[16] Report of the Airborne Laser Program Independent Assessment Team. February 1, 1999. P. 5.

[17] General Accounting Office. Defense Acquisitions, DOD Efforts To Develop Laser Weapons for Theater Defense. GAO/NSIAD, 99-50. March 1, 1999. P. 7.

The Air Force not scheduled to "hot" test the entire PDRR laser sub-system (i.e. all six modules) for power and beam quality until July of FY2002, only 14 months prior to the first scheduled lethal intercept in late FY2003. For the COIL to destroy missiles at hundreds of kilometers it must produce a beam of exceptional quality. If the beam quality is not sufficient, the COIL may not be able to deliver enough energy on the target required to cause the missile to fail during the boost phase.

Based on general scientific principles and estimated laser power levels, beam compensation factors, and the rate of metal heat absorption, CRS has estimated the time it takes to locally heat the missile casing to the elastic (destructive) yield temperature. These estimates are also based upon the range values extrapolated from the ABL experiments at the MIT Lincoln Laboratory in 1997.

These estimates suggest that at the shorter operational ranges, the ABL, if it operates as advertised, is likely be effective against TBM. This estimate is based on remaining boost phase times for 2 mm thick exterior steel casing of the missile .[18] However, at greater operational ranges for similar casings, the time required to destroy the missile may exceed the time left in the boost phase. Given these potential operational limitations, it appears that a fully functional ABL system at longer engagements ranges could be vulnerable to counter measures. For example, a counter measure which lowered the return signals for the tracking and AOS could cause the COIL beam to wander and defocus, and increase the dwell time to longer than the boost phase time. Moreover, if more than one missile is launched at the same time, these estimates suggest that a single ABL may not have the time to engage both missiles at longer operational distances. However, it is important to note that, according to the AF Air Combat Command, ABL exceeds operational range requirement for all classes of scud missilies.

Atmospheric Turbulence

As mentioned above, turbulence in the lower atmosphere (below 12.5 km) will weaken (attenuate) and defocus the laser beams. The Air Force has devoted considerable effort estimating and correcting for this attenuation. The primary approach will be to try to engage the missile above the troposphere utilizing the AOS to compensate for beam distortion (approximately 12.5 km, above 40,000 feet). Below 12.5 km, the Air Force will apply the AOS to the COIL laser beam to compensate for atmospheric defocusing. Based on the earlier work at Phillips Laboratories, the gathering of atmospheric turbulence data (ABLEX and ABLE-ACE tests), and the 1997 Lincoln Laboratory's Firepond experiment, the Air Force is confident that the AOS will meet its basic operational requirements for the ABL.

The IAT noted that the ultimate value of the ABL depends on actual turbulence to be at or below current AF estimated values. However, as noted by the IAT, much of the AF's current turbulence estimates are derived primarily from non-optical measurements in regimes that may not be representative of the anticipated laser beam path of the proposed operational system. The IAT recommended that "the AF

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[18]The details of the estimates and potential time frames for destruction based on missile distances are classified and can not be discussed in the report.

undertake a comprehensive atmospheric measurement program under conditions that more accurately represent the operational environment of the ABL."[19]

The Secretary's response to the IAT findings also noted "that turbulence in excess of the design specification along the slant path between ABL and its intended target can reduce ABL's maximum lethal range and increase dwell times, even at lesser ranges." The complication is that there appears to be no clear method for estimating turbulence levels along a slant path "to a particular threat location at a given point in time."[20] The AF will collect more turbulence data in order to develop tactical options for addressing this issue.

Further, even when operating above the troposphere, at greater operational distances, the curvature of the Earth causes a portion of the laser beam to pass through the troposphere, introducing that turbulence into a portion of the beam path. Consequently, it is likely that at greater operational distances the laser beams will sometimes encounter atmospheric defocusing and attenuation, and may not have enough time to destroy the missile in its boost phase.

To address OSD and congressional concerns about the ability of the AOS to track and compensate for atmospheric turbulence, the Air Force to accelerate a series of tracking and illumination tests from North Oscura Peak (*NOP*) in New Mexico. Using both fixed and moving targets, out to a range in excess of 50 km, a series of comprehensive tests on tracking and the AOS, focusing on beam compensation and scoring will be conducted to validate the operation of these crucial BC/FC subsystems. These tests will scale to ABL engagements of 300 to 400 kilometers in range. However, its important to note that the AF will be utilizing a surrogate laser and replica of the BC/FC system, not the actual hardware that will fly in the ABL.

The Air Force conducted additional AOS testing at NOS in July of 1999 in which a scaled laser was aimed at a target 50km away. The test facility included a functional equivalent of the AOS scheduled for the ABL with scaled mirrors and power to replicate an ABL engagement of a target over a distance of 300-400km. At the conclusion of these tests, the Air Force reported that the laser was able to place sufficient energy on the target with atmospheric conditions three times worse than the ABL is expected to operate in.

The Nose Mounted Turret

This nose turret is made with light-weight composites, carrying the 1.74 meter window and a 1.5 meter mirror, two heavy glass objects (see Figure 1). The turret rotates up to 260^0 in order to direct the lasers toward the target. Weighing approximately 12,000 pounds, the turret attaches to the aircraft from one end with a large ring bearing. That it cantilevers from a pressure bulkhead on the aircraft poses an interesting structural problem. The azimuth overroll gimbal for the turret's field of regard covers the forward hemisphere and aft almost to the wings of the aircraft.

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[19]Op Cit. Secretary of Defense response to IAT report, P. 6.

[20]Op Cit. Secretary's response. P. 9.

Moreover, the turret is shaped and designed to minimize the turbulent boundary layer on the window to preserve the integrity of the laser beam. This is probably a unique structure for an aircraft, somewhat reminiscent of machine gun turrets on World War II bombers.

To address these concerns, a tenth scale model of the turret was built and tested in a wind tunnel to determine how to control the boundary layer to eliminate turbulence that would de-focus the laser beams. A scaled, 20 inch version of the window was made to verify the manufacturing process and the quality of the final window. As long lead items, the initial blanks for the window and mirror have been ordered, and fabrication of the window has begun. The turret, window, and mirror assembly are not scheduled to be incorporated into the integrated COIL, tracking, and AOS testing until the second quarter of FY2001.

Systems Integration

One of the most demanding challenges facing the ABL program is assembling the subsystems into a fully integrated and operating system aboard an aircraft. With the Airborne Laser Laboratory (*ALL*) program in the 1970s and 1980s, the Air Force has had experience assembling a several hundred watt laser and optics system aboard an aircraft. Nevertheless, the ABL multi-megawatt laser and precision tracking system breaks new ground in systems integration. Boeing, the prime contractor, will construct a special system integration laboratory (*SIL*) at Edwards Air Force Base to assemble and test the COIL exactly as it is configured in the aircraft. The facility will have provisions for simulating the behavior of the aircraft and subjecting the COIL to the shake, rattle, and roll it will experience aboard the 747.

While the COIL is being tested in the SIL, the BC/FC system will be installed in the aircraft along with the Battle Management, Command, Control, Communications, Computers, and Intelligence (BMC4I) system and a surrogate laser in place of the COIL (see Figure 2). The integrated system will be fully tested on the ground and in-flight with improvements made as required to bring it to full operational capability.

Large ground-based multi-megawatt lasers (i.e. MIRACLE, NOVA, and NIF (the latter two at the Lawrence Livermore National Laboratory)) all require extremely rigid and stable mounting systems because any small misalignment could cause a catastrophic failure of one or more optical components. Further, high power lasers must be contained in exceptionally clean, stable environments to prevent the destruction of optical components, such as mirrors. The ABL requires that the three laser beams (tracking, beacon, and COIL) be co-aligned to within a few micro meters. No aircraft can provide that level of rigidity and stability needed to maintain the integrity of the ABL, so the plan for the ABL is active alignment. That is, several auxiliary lasers will constantly monitor and reposition key optical components to maintain alignment. The Air Force believes that this system can in real time adjust to the flexing of the aircraft as it flies.

In addition to protecting the optical components, the active alignment system is to assure the precision needed to direct the laser beams at the target missile. The concepts of the active alignment system have been studied and demonstrated in the Lockheed Martin (LM) laboratory brass-board mock-up of the ABL optical system.

LM has demonstrated, under simulated flight conditions, that the active alignment system can maintain the alignment of the BC/FC systems in flight.

Software Development

The computer system and attendant electronics will use commercial equipment, packaged in commercial assemblies. The software is designed and developed in modules and tested in the Boeing Open System Architecture (BOSA) for communications and operating systems.

The software architecture consists of five major components: 1) BMC4I software for the conventional missile detection and IR tracking, and the overall communication and coordination package; 2) Laser control software; 3) BC/FC control software for the optical systems for tracking and adoptive optics; 4) GS, ground support software; and 5) and operational software. This represents a substantial package of first generation integrated software modules that could pose some risk to the overall PDRR schedule.

In October of 1999, the ABL software team successfully demonstrated the the integrated battle management hardware and software systems. This system is designed to ensure that the ABL can accurately detect and identify a ballistic missile and pass that information on to the bean system or another platform if the ABL is out of range. This is the last test in for the "Build-1A," the basic software architecture for ABL's battle management system that controls the six infrared missile search and track sensors.

Field Operations and Life Cycle Costs

The complexity of the ABL would demand considerable field support for its operation. Fuel for the COIL, spare electronics, and spare optical components are required. In addition, to support two ABL aircraft on station 24 hours per day requires a total fleet of seven aircraft with at least four and possibly five aircraft stationed in the theater of operation. The current Air Force estimate for ABL support and operating personnel totals 300. At this time CRS has not seen a cost estimate for the operations.

The Air Force has estimated the costs for engineering, manufacturing and development (EMD) at $1.1 billion and $3.6 billion for the production of seven operational aircraft by the end of 2009. The Air Force estimates $4.4 billion for the 20 year operational cycle for the ABL aircraft. Although single components and commercial components have been shown to exceed derived requirements for the EMD, no subsystem assembly has undergone life-cycle testing in an ABL simulated environment. Consequently, the failure rate and maintenance requirements for components and subsystems in the ABL environment can only be inferred from experience with other systems. In sum, the EMD, production, and life cycle costs, totaling $9.1 billion, are necessarily somewhat uncertain, with true costs undetermined at this time.

Congressional Concerns and Issues

Current Technical Issues

The legacy of the Airborne Laser Laboratory and technology maturation over the past decade have led the Air Force to believe that a multiple, parallel path program (developing and testing key ABL components simultaneously, often referred to as concurrency) is the shortest route to a successful ABL. Therefore, the Air Force has embarked on a program of acquiring long lead items such as the components for the nose turret and the 747 while completing the technology development and fabrication of the COIL and the Beam Control/Fire Control (BC/FC) subsystems. This approach could lead to rapid progress and perhaps lower systems costs, but it has its obvious risks.

The COIL

As previously indicated, the extent to which the COIL laser can engage and successfully destroy an enemy missile in the boost phase is critical to the ultimate success of ABL. According to the AF, past R&D efforts and recent test results suggest that the COIL, as currently designed is capable of destroying missiles at operationally required distances during the boost phase. However, others suggest that significant testing and redesign of the COIL laser will likely be required before the program moves into EMD,[21] primarily because of the immaturity of the technology and the unique environment in which the laser must operate (in an airplane that is constantly flexing and vibrating). If these concerns materialize, the ABL program could experience significant delays that might become very costly if they result in suspension or modification of the long lead procurement items such as the second unmodified 747, the turret window, and the 1.5 meter pointing mirror.

Air Force representatives characterize the COIL as mature technology. While the AF claims that a flight weighted COIL laser module has successfully completed initial testing, reaching 110% of required power and acceptable beam quality, others, including GAO, have questioned the validity of this claim, because the AF has not simultaneously measured the COIL test model beam for power and quality. Again, it is important to note that the COIL must simultaneously produce a beam of sufficient power and quality in order to destroy a missile, at a variety of distances, in limited periods of time. If the COIL laser does not work as planned the AF will not have a usable weapon system. Consequently, Congress could request that the AF conduct a "hot test" (in late 1999 or early 2000, when additional COIL ground tests are already scheduled to occur) of the flight weighted COIL laser in order to assure that the laser can meet both power and beam quality parameters necessary to engage TBMs successfully.

The Air Force argues that the challenges confronting the successful development and deployment of the laser are engineering in nature and can be dealt with over the

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[21] United States Air Force Scientific Advisory Board, Airborne Laser Scenarios & Concept of Operations, SAB-98-04, February 1998, p. 11.

next 18 months according to the schedule. The Air Force is scheduled to test an updated flight model COIL until early in FY2000, and is scheduled to demonstrate its air-worthiness in the third quarter of 2001 (see Figure 4). The first hot fire test of the PDRR COIL laser is scheduled to occur until July of 2002, prior to the 2003 missile destruction test.

In June of 1999, the Air Force ran additional tests of the COIL laser. During these tests, the Air Force reported that the flight weighted laser (FLM) module achieved 107% of required power. Further the laser operated at high power for more than 15 seconds, longer than most anticipated operational laser shots.

In late August of 1999, a 300 gallon tank containing concentrated hydrogen Peroxide (HP) blew up at the TRW COIL testing facility. The FLM was not damaged in the explosion. The HP in the tank was used to cool the testing equipment in the laser, not as a fuel for the flight weighted laser. After the equipment was cooled with HP, basic hydrogen peroxide (BHP) was injected into the laser as fuel for testing the COIL. This procedure was repeated every time the COIL laser was tested.

The Air Force contends that after repeated use of HP, inadequate cleaning of the flow tubes may have allowed the HP to contaminate the BHP, which is used to power the COIL laser. Air Force officials note that this would not occur in the actual ABL system because BH would be run through the laser before the aircraft takes off and not reused. However, Victor George, a scientist with over 30 years of experience in designing and building lasers noted that if the contamination came from the main laser's mixture of BHP and not from not from a contaminate due to the reuse of BH, such an occurrence would be troubling.[22] The Air Force argues that there is no proof that the BHP was the source on the contamination.

Beam Control / Fire Control

As described earlier, the BC/FC includes the missile precision tracking (both internal to the 747 and external) subsystems, and the AOS beam compensation subsystem.

A major technical issue is the successful development of the AOS. The ultimate success of the AOS is dependent on the extent to which the Air Force computer models accurately characterize atmospheric turbulence in order to "correct" beam distortion. The purpose of the AOS is to modulate the shape of the laser beam in order to compensate for the distortions introduced by the atmosphere and thus keep maximum beam power focused on the target.

Based on its atmospheric turbulence experiments (e.g. ABLEX (1993), ABLE-ACE (1995), Firepond (1997)),[23] and other experiments, the Air Force contends that it has collected sufficient atmospheric turbulence data to develop accurate computer

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[22] *Explosion Raises Questions Over Airborne Laser*, New Technology Week. Oct. 12, 1999. P. 12

[23] A succession of experiments the Air Force carried out to test and validate the concept of adoptive optics for ABL applications.

simulated models of atmospheric turbulence. The program director of ABL contends that there is a strong correlation between their computer generated turbulence models and the actual atmospheric turbulence data the Air Force has been collecting for the past five years. The Air Force is confident that its atmospheric compensation models will permit the COIL to shoot down a missile at various distances in a variety of atmospheric conditions. The Air Force has programs in place to continue the G21 collection of atmospheric data and update its algorithms, and for studying advanced concepts in beam compensation.

Others, including the IAT, have argued that the Air Force has not collected sufficient atmospheric turbulence data to operate the ABL in a variety of potential conflict scenarios. While recognizing that the ABL might be effective against targets at nominal ranges in ideal weather conditions, the Air Force Scientific Advisory Board (SAB) suggested that " the ambitious character of the compensation design, together with the incompleteness of the turbulence data... gives rise to legitimate uncertainty and even skepticism about the ultimate feasibility of delivering adequate irradiation on target." The SAB suggested that the Air Force collect more atmospheric data in order to document what is "known and unknown about turbulence and the assumptions made in modeling the weapon performance."[24] The IAT strongly endorsed the need to collect more atmospheric turbulence data.

As previously indicated, AOS is relatively new technology although it has been widely implemented in modern astronomy. The Air Force has successfully utilized such technology for a variety of astronomical purposes at its Starfire Optical Range. The Air Force contends that its success in aiming a laser at a target in space and utilizing computer controlled deformable mirror to compensate for atmospheric distortion demonstrates that AOS will be successfully deployed in the ABL.

However, astronomers have pointed out that the AOS system employed for the ABL is far more complicated than those used in astronomy. They note that astronomers are pointing a single laser vertically through a turbulent thin vertical layer of atmosphere, typically 15 km-60 km, as compared to hundreds of kilometers of atmosphere the three ABL lasers would have to propagate through. Further, while astronomers have their lasers and AOS mounted on top of a concrete slab, the ABL AOS must make rapid, critical beam adjustments while operating in a moving airplane that will be subjected to significant turbulence and vibration as it travels through the atmosphere.

The Air Force has conducted a number of experiments to determine how atmospheric turbulence distorts the COIL laser beam, and the extent to which the AOS can "correct" the distortion. In one such experiment, Firepond, MIT's Lincoln Laboratory demonstrated that at a short range (5.4 km), utilizing computer controlled tracking test on a static target, the beam compensation improved by a factor of four utilizing an AOS. According to the Air Force, the experiment was designed to simulate ABL flight conditions for ranges over most of the system's projected battle space.

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[24]United States Air Force Scientific Advisory Board, Airborne Laser Scenarios & Concept of Operations, SAB-98-04, February 1998, p. 10.

Nevertheless, Congress, DOD in response to the IAT report, and the Air Force's SAB have expressed concern about the adequacy of such tests, given the experimental nature of AOS technology. In its FY1999 defense appropriations Act, Congress instructed the Air Force to accelerate testing of its AOS. The SAB noted that beam control and turbulence compensation testing should "document and describe the technical features of the design and the uncertainties that need to be tested...tests that will demonstrate or resolve the issues and the schedule for the testing."[25] In response to these concerns the Air Force has scheduled a series of tracking and beam compensation tests from North Oscura Peak (*NOP*) in New Mexico. Using both fixed and moving targets, out to a range of 50 km, the Air Force will conduct comprehensive tests on tracking and beam compensation. Electronic scoring will be conducted against airborne target boards mounted to an aircraft flying at scaled ranges and velocities to represent ABL attack scenarios. These tests will utilize a surrogate tracking laser and AOS (positioned on the ground), to validate the operation of the ABL BC/FC system. Additional tests, utilizing the same surrogate subsystems, will be conducted against missile targets in FY2000.

Another issue which has not been raised extensively is the tracking accuracy of the ABL beams. In order to keep the beam focused on the missile, the ABL system must maintain a very precise (on the order of a few microns) alignment of the optical

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[25]United States Air Force Scientific Advisory Board, Airborne Laser Scenarios & Concept of Operations, SAB-98-04, February 1998, p. 11.

ABL PDRR Schedule

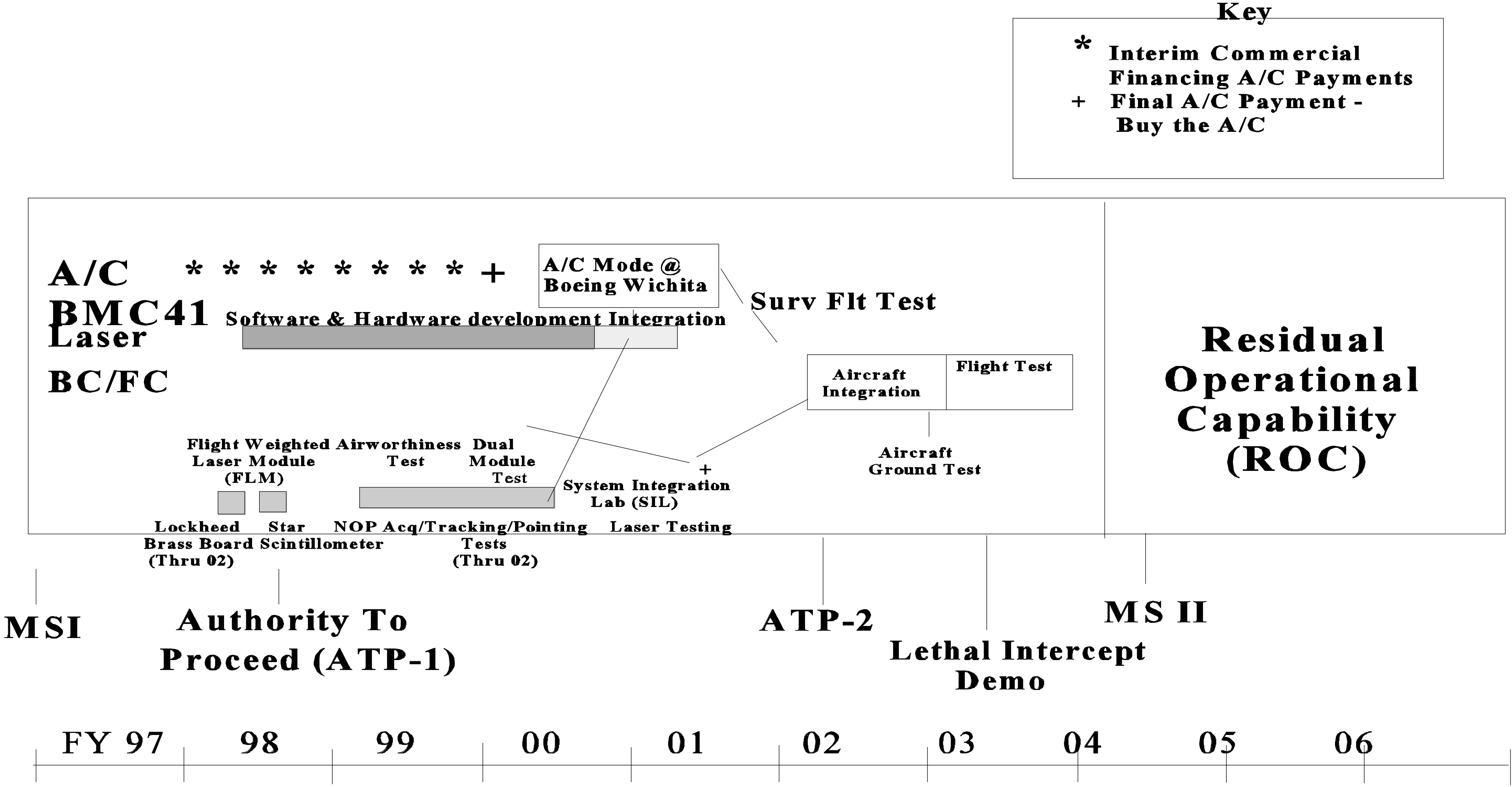

Figure 4, Chart created by CRS based on Air Force documents.

components mounted in the aircraft. The technique for maintaining this precision is to have an internal alignment laser and optical components to make rapid, precise adjustments to the three laser beams to keep them co-aligned. The design has been tested in the laboratory, but the "reality" testing will occur when the BC/FC system is mounted in the aircraft which is scheduled for the third quarter of FY2002. The stability of this alignment system is crucial to the success of the ABL.

ABL Testing

As described at the start of this section, the Air Force has embarked upon a dual path program of engineering and fabrication of key technologies, and the acquisition of long lead components. The 747 has a 24 month delivery time and the turret window has a lead time of 36 months. These lead times have implications for the EMD phase of this program. The testing regimen for the PDRR derives from this context (see Figure 4).

Congress has expressed concerns about the adequacy and timing of the ABL testing program. In its FY1999 defense authorization report, the Senate Armed Services Committee (SASC) noted that much of "the testing necessary to make well informed judgements about the technical viability of the ABL program will not begin to occur until fiscal year 2002, just prior to the program entering EMD."[26] (In actuality, long lead purchases and design work for the EMD phase commences in the fourth quarter of 2002, the year before the final testing of the PDRR program). The Committee also noted that the first time the Air Force plans to collect optical data on the performance of a laser fired horizontally through the atmosphere is during the last quarter of fiscal year 2002, during its first attempt to shoot down a missile just prior to milestone II review.[27] Some Air Force officials have expressed concerns about the testing protocols because many of the tests, prior to FY2002, do not involve the actual hardware that will be flown on the ABL. They have noted that integration testing of the AOS and the COIL is not scheduled to occur until September of FY2002.

Air Force documents state that its PDRR testing program is designed to demonstrate that key ABL technologies are mature and ready for an ABL weapon system. The scope of the testing is gradually increased, going from proving components, to integrating components, to proving subsystem, to full systems testing. The Air Force says that these subsystems had been demonstrated previously to adequate levels of proficiency either individually or in another application and that earlier Airborne Laser Laboratory success has provided a valuable legacy of working with airborne lasers.

While the PDRR testing plans characterize certain key subsystems of ABL as mature technology ready for the insertion into the ABL, others disagree. The Air Force Scientific Advisory Board (SAB) characterized ABL key technology (AOS and

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[26]Senate Armed Services Committee, *National Defense Authorization Act for Fiscal Year 1999*, 105th Cong., 2nd sess., 1998, S. Rpt. 105-189. P. 136.

[27]Ibid., P. 137

the COIL) as "experimental systems."[28] Others have pointed out that "mature" technology means a capability that has proven itself numerous times under a variety of circumstances.

The IAT stated that "given the large investment in the initial flight test system, the stated PDRR objective of demonstrating a representative TBM target kill appears too limited." Given the size of the PDRR investment, the IAT suggested the ABL PDRR should expand its testing protocols in order to gather additional data and expand the test envelope for both the aircraft and targets.[29] DOD's response to the IAT noted that while additional testing will increase near-term costs and delay ABL's initial operational capability (from 2008 to 2009), the added tests will ensure that the expenditures required for the ABL's EMD phase are justified.[30]

While the expanded ABL testing program may help the Air Force gain valuable knowledge about critical subsystems, in most instances the tests will not utilize the actual hardware that will fly on the PDRR ABL. In order to address congressional concerns, as well as other program critics, the Air Force could utilize as much actual PDRR hardware as possible in its future testing. For example, this could include within practical feasibility, demonstrating AOS capabilities during North Oscura Peak testing scheduled to begin in 1999 and continue into 2000.

ABL PDRR Schedule

Another issue closely aligned with testing is the challenge of integrating all of the major ABL subsystems. The Air Force has recently revised its integration schedule, strengthening the ABL test protocols by adding additional PDRR tests focusing on beam control, atmospheric compensation utilizing AOS risk reduction in beam control, and atmospheric characterization. (see Figure 5).

Despite these additions, overall systems integration remains a formidable challenge. While the Air Force has delayed initiating systems integration activities by a year, the time period for completing systems integration activities remains essentially the same. Aircraft integration will begin the fourth quarter of FY2001 with the BMC4I[31] system. At this time the BC/FC will be installed in the aircraft along with a surrogate for the COIL. This almost complete ABL system will be flight tested and made ready for the COIL by the third quarter of FY2002. Beginning in the fourth quarter of FY2001 the Air Force plans to assemble the COIL in the systems integration laboratory (SIL). The COIL will be assembled and subjected to in-flight conditions in the SIL while the BC/FC is undergoing its flight tests. Then the COIL will move on to the aircraft in the first quarter of FY2003. This will be the first time all of the major subsystems of the ABL will be tested as an integrated weapon system.

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[28]United States Air Force Scientific Advisory Board, Airborne Laser Scenarios & Concept of Operations, SAB-98-04, February 1998. P. 10.

[29]Op Cit. IAT, p. 5.

[30]DOD's response to the IAT report. P. 6.

[31] BM/Battle Management, C^4I/Command, Control, Communications, Computers and Intelligence

This allows about six months before the ABL is scheduled to shoot down a missile during flight tests.

This would appear to be a very aggressive schedule for both the key technologies and the system integration and testing prior to the flight tests. The SAB report, of February 1998 on the ABL, expressed reservations about the PDRR schedule.

> The program evolution as currently planned is rational in its sequencing of tests, but the schedule appears to be unrealistically brief in the flight test phase. Past experience with high power laser systems and large beam directors suggests that new and difficult problems will surface in that phase, and many flights and targets will be needed to sort them out. It would be advisable for the SPO to develop contingency plans to prepare for the possibility that the current success-oriented schedule is not achieved.[32]

This would also be the first time that the system's operational software would be tested. The SAB study is about one year old and although the program has made significant progress since its release, the integration phase is often the most critical in any project. Any significant delays caused by underperformance in the project will likely increase its overall cost.

Regarding the EMD, the Air Force has scheduled procurement of the long lead components and design efforts to commence in the fourth quarter of FY 2002. This includes the purchase of the second unmodified 747 aircraft. Under this schedule, the Air Force would be committed to buying a second modified 747 one year before the flight test and evaluation phase for the PDRR is completed, including the actual shooting down of a missile in late FY2003. Moreover, the aircraft will not be modified until one year after PDRR demonstrations are complete. This could be an issue for Congress and the independent review team to consider. A second window was purchased under the PDRR program as a risk reduction backup for an item with a 36 month lead time. Unless the PDRR program should need the second window, it will be used for the EMD phase of the project.

Counter Measures

An issue that appears to be receiving greater attention in Air Force ABL documents is a discussion on counter measures that an adversary may employ to reduce or defeat the intent of the ABL. While much of this discussion would necessarily occur in a classified environment, the Air Force SAB has recommended that the Air Force improve its response to both current and long term counter measures. Others have suggested that since the ABL is not scheduled to be operational until 2009, it seems reasonable to expect that the Air Force should examine the potential evolution of both technical and tactical counter measures.

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[32]United States Air Force Scientific Advisory Board, Airborne Laser Scenarios & Concept of Operations, SAB-98-04, February 1998, p. 10.

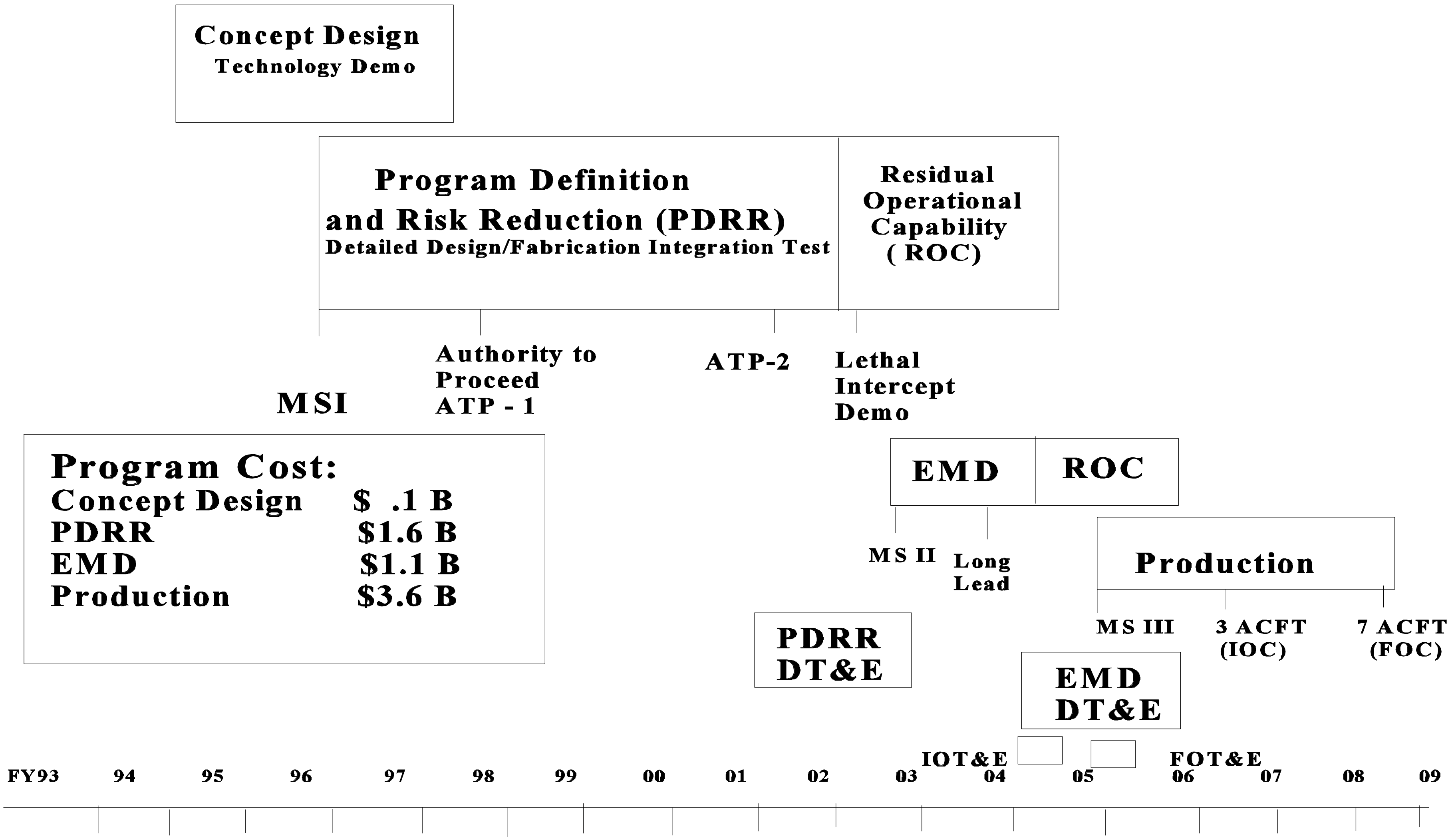

Figure 5, CRS chart based on information from the Air Force.

In the near term, the Air Force might want to examine the prospects of an adversary applying a very high polish on the outer casing of the missile, in an attempt to make tracking and targeting more difficult. In the long term, the SAB and others have argued that potential adversaries could harden existing or new TBM against attack. They could also build a new missile that has a shorter boosting time, thus reducing potential ABL engagement times, or employ early release of sub-munition payloads. However, it is important to note that the ABL design may make it a more effective weapon against missiles carrying submunitions than other TAMD systems.

Another counter measure would be to spin the missile when it is launched which then could take longer to destroy because of laser heat dispersion.[33] In terms of tactical counter measures the enemy could launch missiles from ranges beyond ABL's striking ability, or quickly move a missile and attack before the ABL is deployed. In most instances a potential adversary would be likely to employ a mixture of technical and tactical counter measures which could seriously compromise the operational capability of the ABL. The IAT recommended that the AF undertake an aggressive test and analysis program to “gain a thorough understanding of the effectiveness of such counter measures. This information will be needed to support an informed Milestone II decision at the conclusion of PDRR.[34] “

In September of 1998, the Air Force announced that it is forming an independent Directed Energy Countermeasures Assessment Team (DECAT) to examine potential technical and tactical counter measurers that might be employed by an adversary to defeat the ABL. The director of this team will report to Air Force Headquarters, not to the Director of the ABL program office. Nevertheless, key congressional committees may want to participate in closed briefings with the Air Force, and other independent experts, to examine the potential short and long term operational consequences of various technical and tactical counter measures likely to be employed against the ABL. The Air Force and/or Congress could request the LCAT to develop potential counter measure tactics that could be deployed and tested during the latter stages of PDRR testing.

The recent acknowledgment that the Russians are developing a new surface to air missile (SAM) with a range of 250 miles raises serious operational counter measure concerns for the ABL. The 250 mile range is 10 times the range of SAMs used in Kosovo that made it difficult for U.S. military commanders to successfully prosecute the air campaign. Referred to as the S-400, the 250 mile SAM is not scheduled to be operational until 2005. According to individuals inside and outside of the Pentagon, the new SAMs’ extended range will require important platforms such as the ABL to “stand off”much further than originally planed when shooting at missiles.[35]

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[33]United States Air Force Scientific Advisory Board, Airborne Laser Scenarios & Concept of Operations, SAB-98-04, February 1998, p. 7.

[34]Op. Cit. IAT Report. p.7.

[35] John Donnelly, Defense Week, Sept. 27,1999. *Coming SAMs have 10 Times Grater Range Than Today’s,* Vol. 20, Number 38. P. 14.

However, Air Force officials note that the Service has not lost any high-value assets such as the Boeing E-3 Airborne Warning and Control System (AWACS) or the Northrop-Grumman E-8 Joint Surveillance Target Attack Radar System (Joint STARS) to a SAM or fighters since such systems became operational. The Air Force contends that it is capable of protecting the ABL from similar threats that have confronted AWACS and Joint STARS. Nevertheless, these systems have not had to confront SAMs with greater ranges, speed and the ability to engage 6 separate targets.

FY1999 Authorization and Appropriations

Congressional questions have been raised about the ABL program from its inception. In FY1994 Congress raised concerns about the Air Force's request of $3.845 million for airborne laser technology development. The FY1994 Senate appropriations report denied the request stating that "a recently released study on Boost Phase Intercept (BPI) determined that ABL was one of the riskiest approaches to attacking ballistic missiles immediately after launch." The report also noted the $773 million cost to develop an ABL demonstrator through FY2001 was not affordable. Congress appropriated $1.945 million for ABL technology in Fy1994, with the stipulation that the Secretary of the Air Force provide a rationale for pursuing this technology and documentation that the program is fully funded in the Future Years Defense Program.[36]

Essentially, past congressional concerns have centered around two main issues that were raised in the Senate's FY 1997 Defense Authorization report. The first is that the Air Force had not adequately demonstrated (through testing) that the key technologies were ready to be assembled into an ABL. And second, that the ABL concept of operations would not allow "the system to be cost and operationally effective." In regard to the second issue the Committee wrote that in terms of operations " the ABL will be forced to stand off approximately 90 kilometers from the forward edge of the battle area... but the ABL will have a range well below 500 kilometers...in most cases below 300 kilometers. This means that the ABL will have very little capability against short-range (300 km) missiles and longer-range missiles launched from significant distances behind the forward edge of the battle area."[37]

In its FY1999 defense authorization report, the Committee again raised these two issues, noting that "the Air Force had not adequately demonstrated the feasibility of the necessary technology to begin such significant investments." The report stated that the testing necessary to make important decisions about the technological viability of the ABL program will not occur until FY2002, just prior to ABL entering EMD. [In fact PDRR flight testing is one year following budget commitments to

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[36]Conference Committee, *Making Appropriations for the Department of Defense for the Fiscal Year Ending September 30,1994, and Other Purposes.* 103 rd Congress 1st sess., 1993 H. Rpt. 103-339. P. 134.

[37]Senate Armed Services Committee, *National Defense Authorization Act for Fiscal Year 1997*, 104th Cong., 2nd sess. 1996, S. Rpt. 104-267. P. 180.

EMD (see figures 4 & 5).] The Committee again questioned the cost and operational viability of the program.[38]

The authorization conference report instructed the Secretary of Defense to form an independent assessment team (IAT) of experts from outside of the DOD to review the technical and operational aspects of the ABL program. By March 15, 1999, the IAT was to assess the following:

> 1) Whether additional ground testing or other forms of data collection should be completed before initial modification of the commercial aircraft to the ABL configuration;
> 2) The adequacy of exit criteria for the program definition and risk reduction phase of the ABL; and
> 3) The adequacy of current ABL operational concepts.[39]

The report also reduced the $292.2 million request by $57 million, recommending $235.2 million, and limiting FY1999 spending to $185 million until 30 days after the Secretary of Defense submits the IAT report to Congress. The IAT report was submitted to Congress on March 9, 1999.

Senate appropriators have also called for additional testing of the COIL laser prior to proceeding to system integration activities in FY2001. In its FY1999 appropriations report, the Committee stated that the Air Force has failed to demonstrate propagation and lethality of the COIL. The FY1999 Appropriations Conference Report directs the Air Force to "conduct a meaningful ground demonstration of the capability to produce a high energy beam, compensate the beam for atmospheric disturbances, and measure the deposition of laser energy on a target under realistic test conditions. "[40] The Conferees reduced the budget request by $25 million to $267.2 million to reduce concurrency in the program and to incorporate lessons learned from the tests back into the ABL program.

The Air Force contends that its testing program has been carefully structured to ensure that the critical risk areas associated with the various ABL subsytems have been properly characterized through a prudent testing and evaluation process. The Air Force states that the ABL subsystem test plan will address all the issues raised by Congress prior to the start of systems integration activities in 2002. For example, in response to the appropriators' call for additional testing of the lasers and AOS, the Air Force will accelerate its planned time table for the NOP tests on a mock-up of the BC/FC subsystem and a surrogate high power laser from early in 2000, to the beginning of 1999. The COIL laser will undergo a long series of tests at each stage

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[38]Senate Armed Services Committee, *National Defense Authorization Act for Fiscal Year 1999*, 105th Cong., 2nd sess., 1998, S. Rpt. 105-189. P. 136.

[39]Conference Committee, *The Strom Thurmond National Defense Authorization Act for Fiscal Year FY1999*, 105th Cong., 2nd sess., 1998, H. Rept. 105-736, P. 32 and 33.

[40]House Committee on Appropriations, *Making Appropriations for the Department of Defense for the Fiscal Year Ending September 30, 1999, and for Other Purposes.*105th Cong., 2nd sess. 1998, H. Rpt. 105-746. P. 148.

of development culminating in a full, six module subsystem in the SIL by midyear of 2002.

In response to Congress, and the findings of the IAT, the Air Force has expanded ABL's testing and risk reduction activities, adding more flight tests, and more attempts at shooting down TBM representative targets under a variety of operational circumstances (not just a single "representative target") before recommending moving ABL to EMD in FY2004. According to the Air Force, the $25 million reduction and the call for more testing has led to a 12 month delay in some elements of the program, and an estimated cost increase of $300 million for the PDRR.

FY2000 Authorization and Appropriations

As part of the FY2000 defense authorization bill (P.L. 106-65) Congress took additional steps to reduce concurrency (developing and testing key ABL components simultaneously, versus developing and testing key components one-at-a-time or sequentially) in the ABL program. The Senate Armed Services Committee report (S. Rpt. 106-50) noted that the Secretary of Defense must develop an acquisition strategy for the ABL that strikes an appropriate balance in managing risk and concurrency. The legislation instructs the Secretary of the Air Force not to begin modification of the PDRR aircraft (which Boeing delivered in January of 2000) until the Secretary of Defense certifies to Congress that test and analysis results based on the following activities:

1. The North Oscura Peak dynamic test program;
2. Scintillometry data collection and analysis;
3. The contermeasures test and analysis effort;
4. The letality/vulnerability program; and
5. Reduction and analysis of other existing data.[41]

Congress wants to be sure that all the ABL major subsystems meet minimal operational requirements before the PDRR plane is modified. Any modification could prevent the Air Force from returning the plane to Boeing if a major technical obstacle arose during PDRR testing.

Congress also instructed the Air Force not to modify the second aircraft (The EMD plane with a scheduled delivery date of 2003.) until the PDRR plane "successfully completes a robust series of flight test that validates the technical maturity of the ABL program and provides sufficient information regarding the performance of the system across the full range of its validated operational requirements."[42] Modification of the EMD aircraft was scheduled to begin prior to the completion of PDRR testing, including the actual destruction of a theater ballistic missile in 2003.

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[41]Senate Armed Services Committee, *National Defense Authorization Act for Fiscal Year 2000*, 106th Cong., 1st sess., 1999, S. Rpt. 106-50. P. 149.

[42]Op. Cit. S. Rpt. 106-50. P. 150.

Conclusion

The current PDRR testing schedule is likely to present Congress with a series of difficult decisions. First, as previously discussed, given the uncertainties surrounding the COIL, Congress may wish to request that the AF "hot fire" the PDRR laser in order to simultaneously measure beam power and quality, rather than waiting until FY2002 when the PDRR laser is scheduled to be "hot tested" in the SIL, and on the airplane in FY2003.

Second, under the current schedule, the Air Force is to purchase a second modified 747 one year before PDRR flight tests of all the major subsystems are completed. Given concerns expressed about the maturity of crucial ABL technologies, Congress may consider delaying the purchase of a second aircraft until after PDRR testing is completed. Nevertheless, postponing the purchase of long lead items would predictably lead to additional cost increases and delays in deploying the ABL. It is important to note that modification of the 747 begins a year after the Air Force places its order for the plane. This raises the possibility that if the Air Force were to order the plane as scheduled, Boeing could take the plane back for commercial sale if ABL is delayed indefinitely, (prior to the actual modification of the plane) at no or minimal cost to the government.

A third major issue Congress may face centers around the future of the ABL program and laser weapons in general. As indicated in this report, there is some concern that the ABL may not be capable of demonstrating that it can meet the Air Force's operational requirements as it moves to engineering, manufacturing and development (EMD). Given that the Air Force will have spent over $1 billion on the ABL before entering EMD, Congress could decide to extend the PDRR testing schedule until the ABL demonstrates that the system will be capable of meeting its operational requirements. Or, if the ABL encountered considerable science and technology challenges during PDRR testing, Congress could consider using the ABL as a research and development (R&D) platform that may eventually lead to the establishment of a different or reconstituted ABL acquisition program.

Fourth, given the desire in and outside Congress to develop laser weapons, Congress may want to pursue the R&D option even if the Army's and Navy's upper and lower tier TAMD are likely to be operationally ready prior to the deployment of the ABL. Unlike other TAMD systems, if ABL works as advertised, it may be better designed for destroying missiles carrying submunitions, before the submunitions are deployed.

Fifth, if ABL PDRR testing reveals a number of significant scientific and technical challenges, Congress could decide to cancel the ABL program. If this occured, Congress could then instruct the three Services and the Defense Advanced Research Projects Agency to initiate a number of research and development activities that would eventually lead to a variety of laser based weapons.

Finally, Congress could decide that the current reconfigured ABL program reduces risks to sufficient levels that would allow the program to proceed to its expanded PDRR flight tests schedule in FY2003. With additional testing, the collection of additional atmospheric data and the validation of the AOS compensation capabilities, Congress and the Air Force could decide that the only practical way of determining if the ABL will work as designed is to flight test the PDRR plane against a variety of targets.